The Abdus Salam
International Centre
for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

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13 - 24 August 2012

Synchrotron radiation and some techniques

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France

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Synchrotron radiation and some techniques

Wim Bras

DUBBLE @ ESRF

Netherlands Organisation for Scientific Research

- Short introduction to synchrotron radiation
- What is a beam line?
- Examples of experiments

- I’ve tried to keep everything without formulas but only explain the basics
- There are plenty of books full of formulas

Meet the Röntgens

Prof. Conrad Röntgen
First Nobel price winner

Mrs. Röntgen

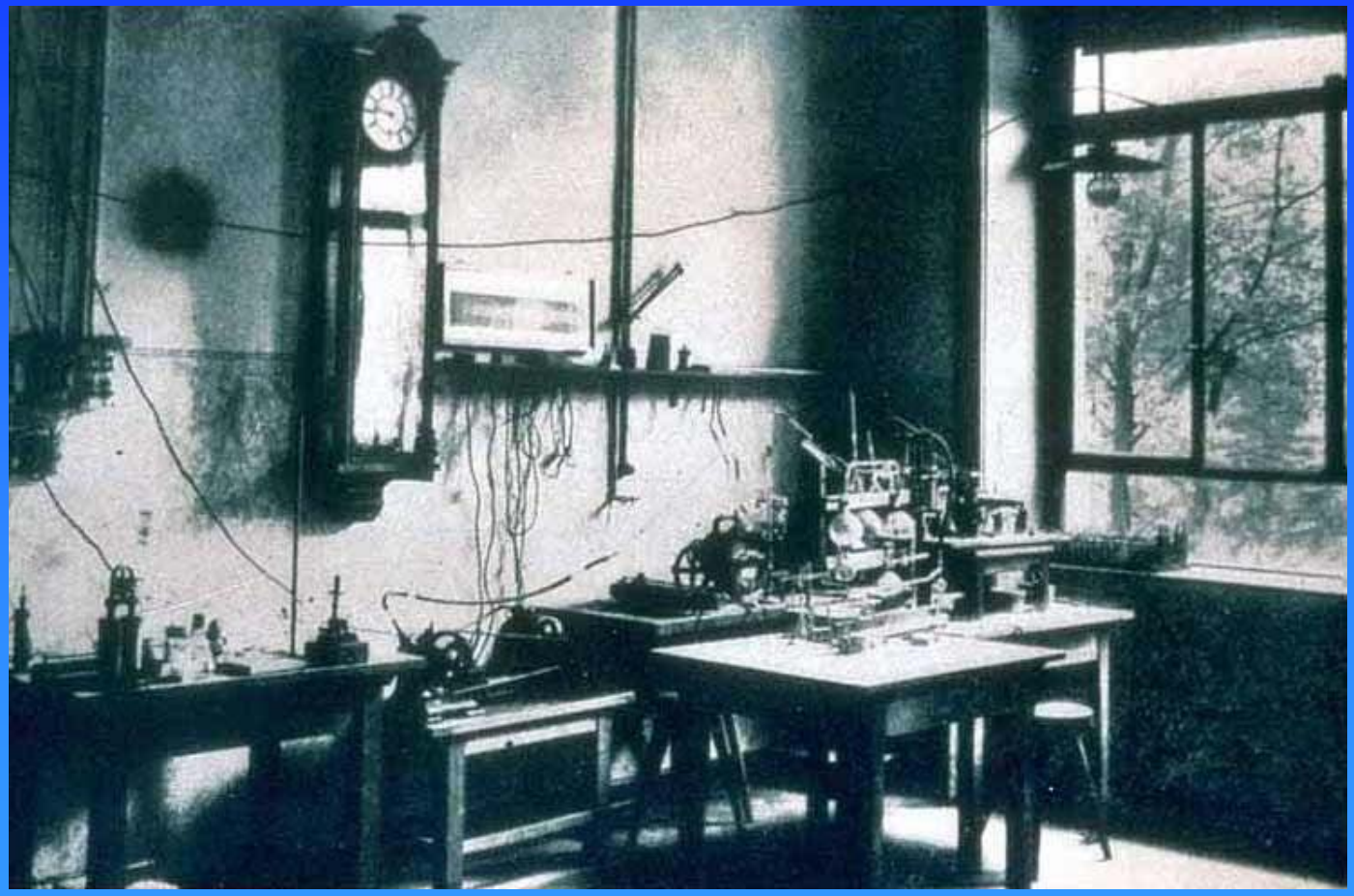
Röntgen's 16 year old son

How do we conventionally generate Röntgens?

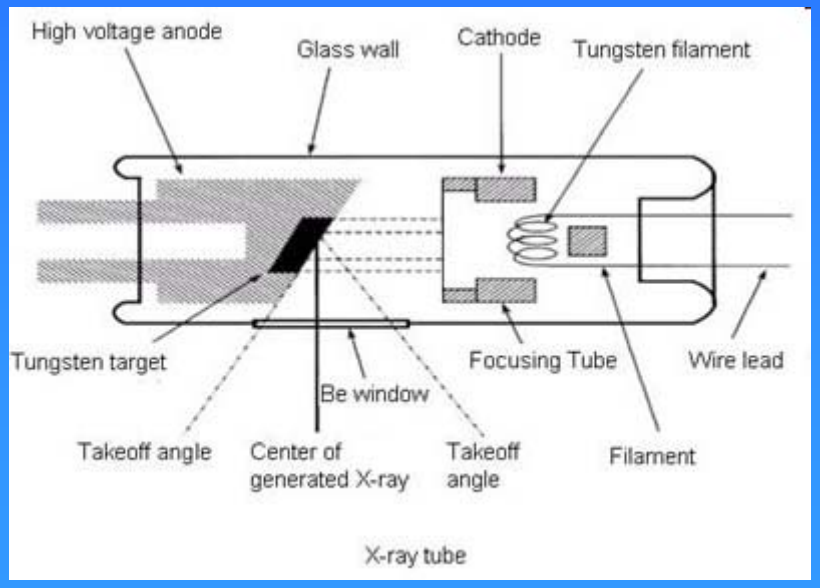
- With an X-ray generator
  (in laboratory)
- Radioactive source
  (mainly in hospitals)
- Synchrotron radiation

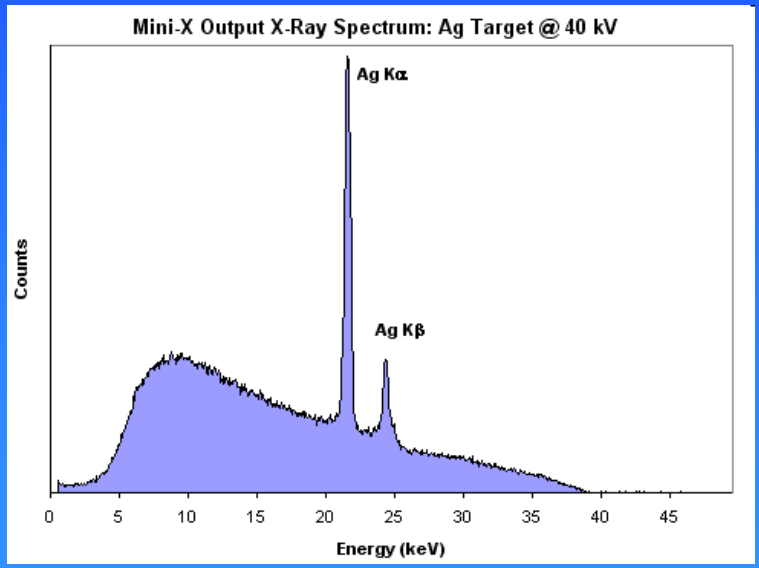
Panalytical Almelo

An early X-ray laboratory



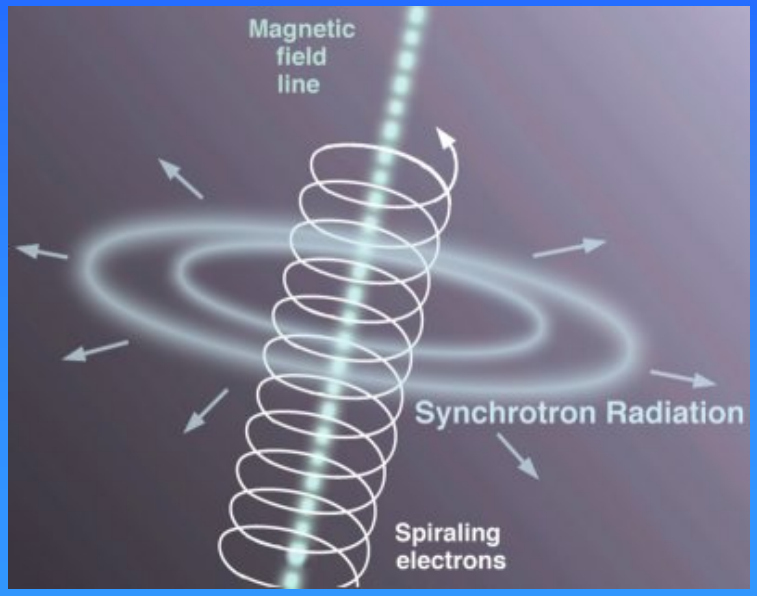
“Conventional” X-ray tube





Synchrotron radiation

- X-rays generated by fast moving electrically charged particles forced to change their direction
- Natural phenomenum



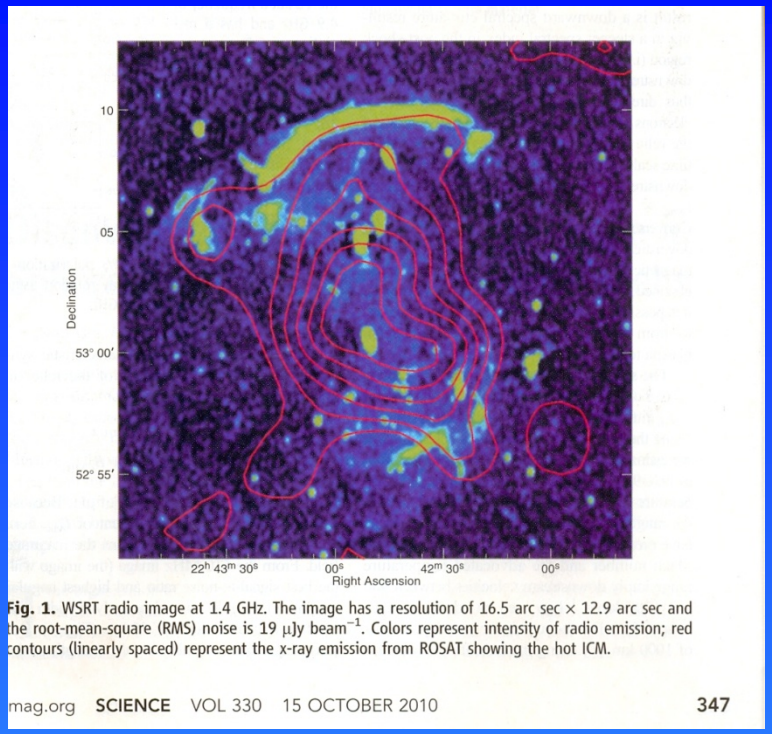
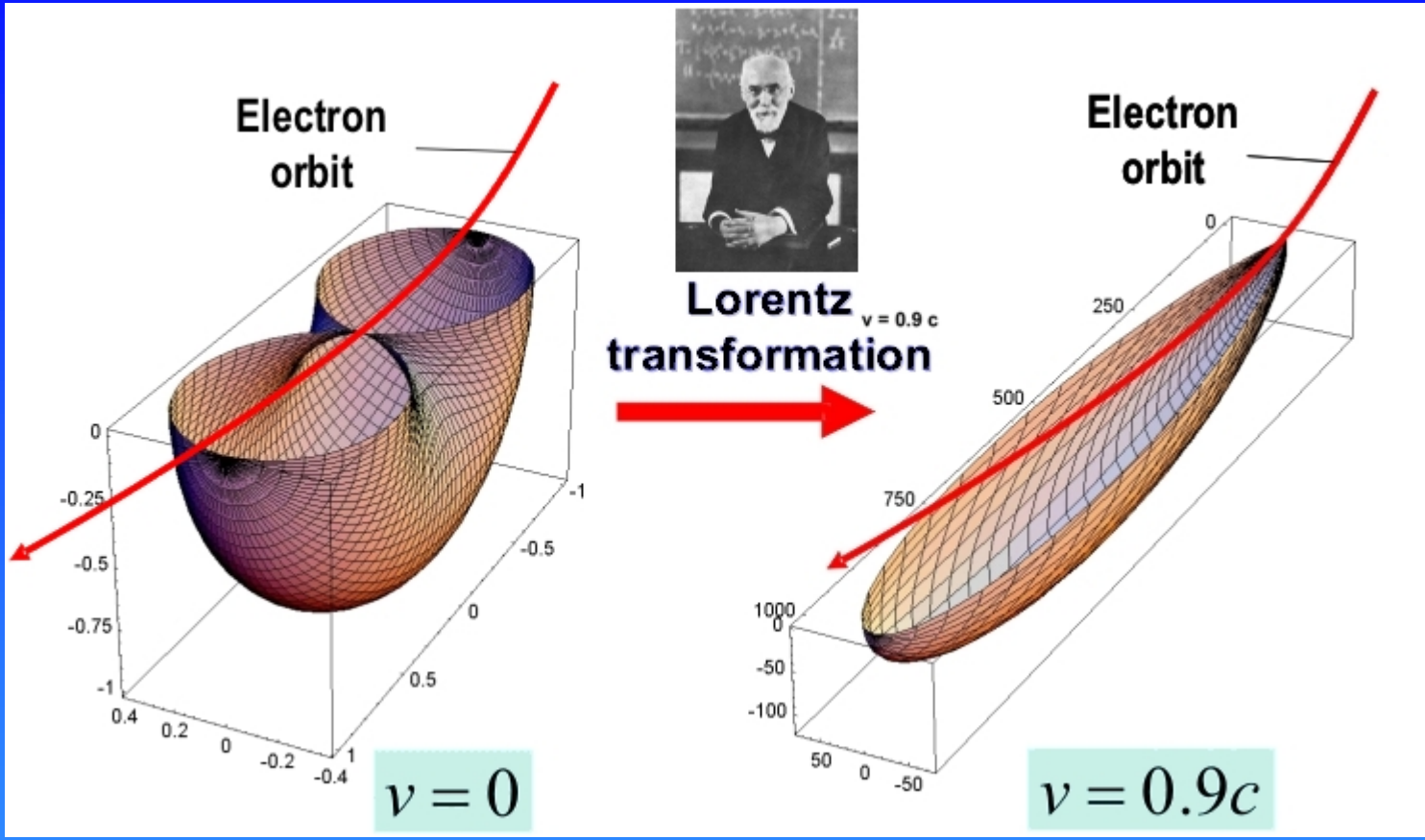
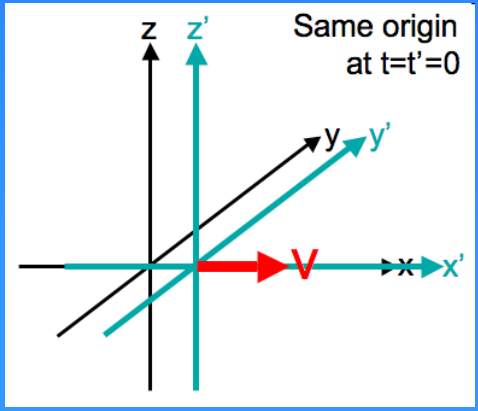


Fig. 1. WSRT radio image at 1.4 GHz. The image has a resolution of 16.5 arc sec × 12.9 arc sec and the root-mean-square (RMS) noise is 19 μJy beam^{-1}. Colors represent intensity of radio emission; red contours (linearly spaced) represent the x-ray emission from ROSAT showing the hot ICM.

Synchrotron radiation map
of two colliding solar systems

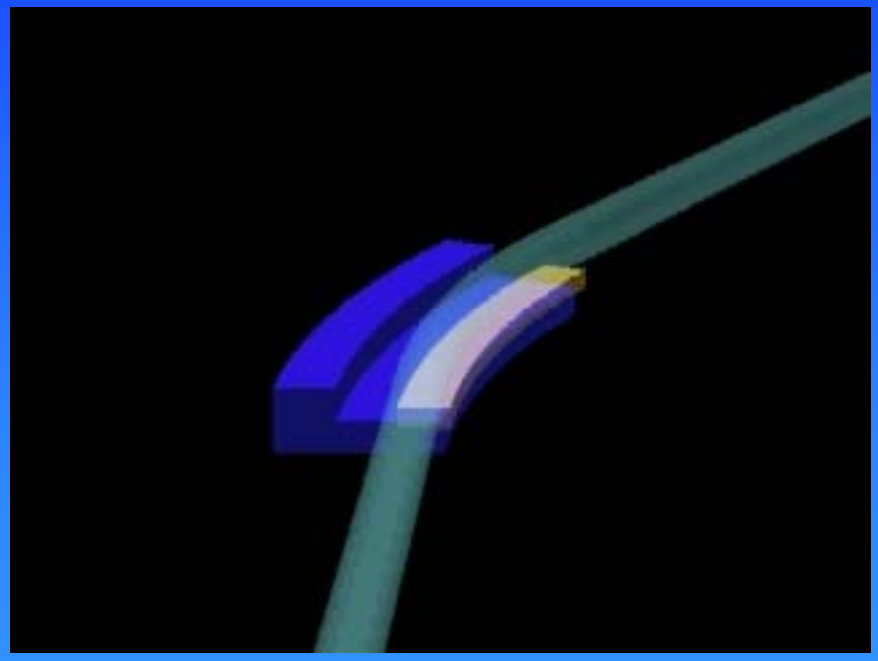


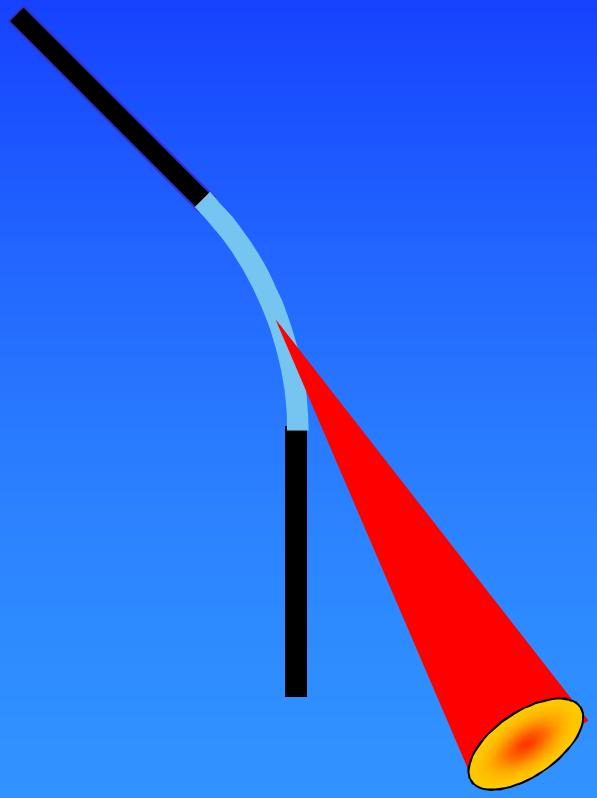


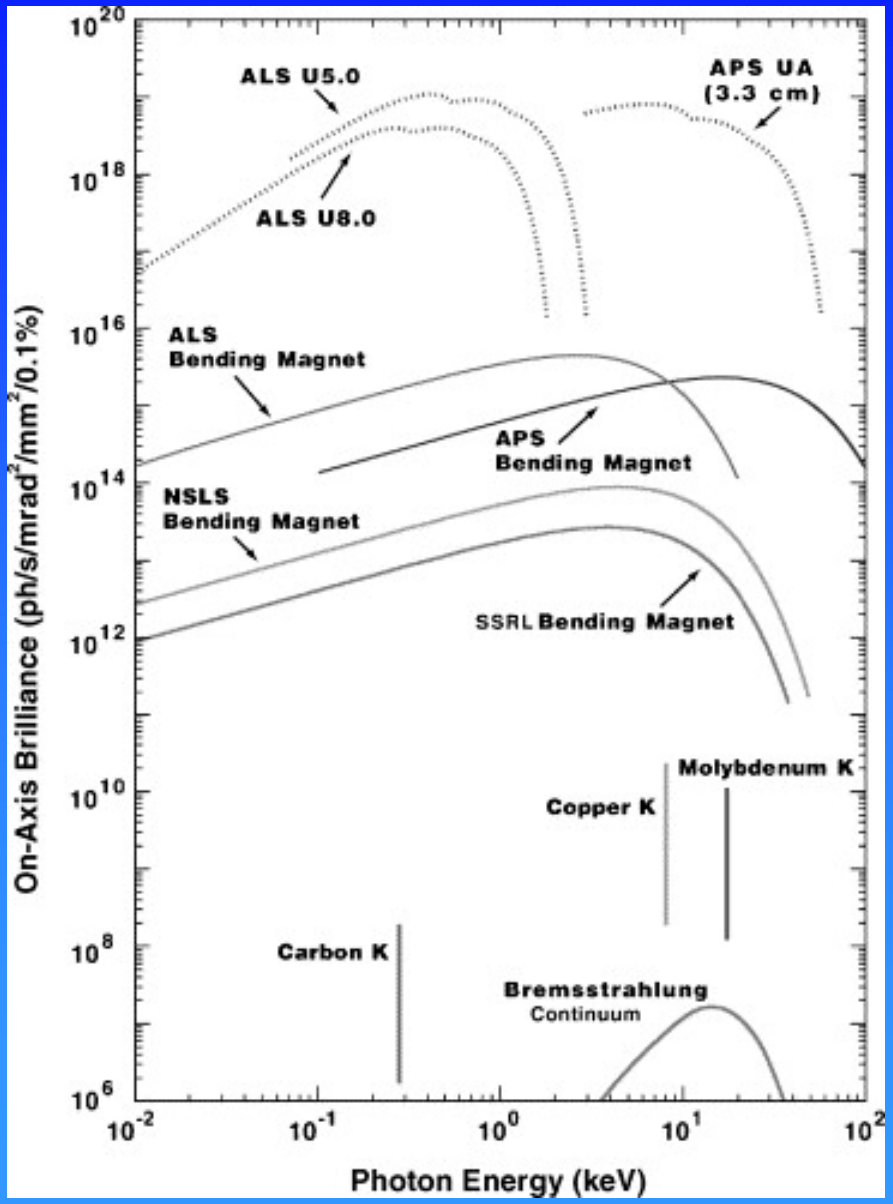
$$\begin{cases} t' &= \gamma\left(t - vx/c^2\right) \\ x' &= \gamma\left(x - vt\right) \\ y' &= y \\ z' &= z \end{cases}$$

Lorentz transformations

Synchrotron radiation sources







Concepts:

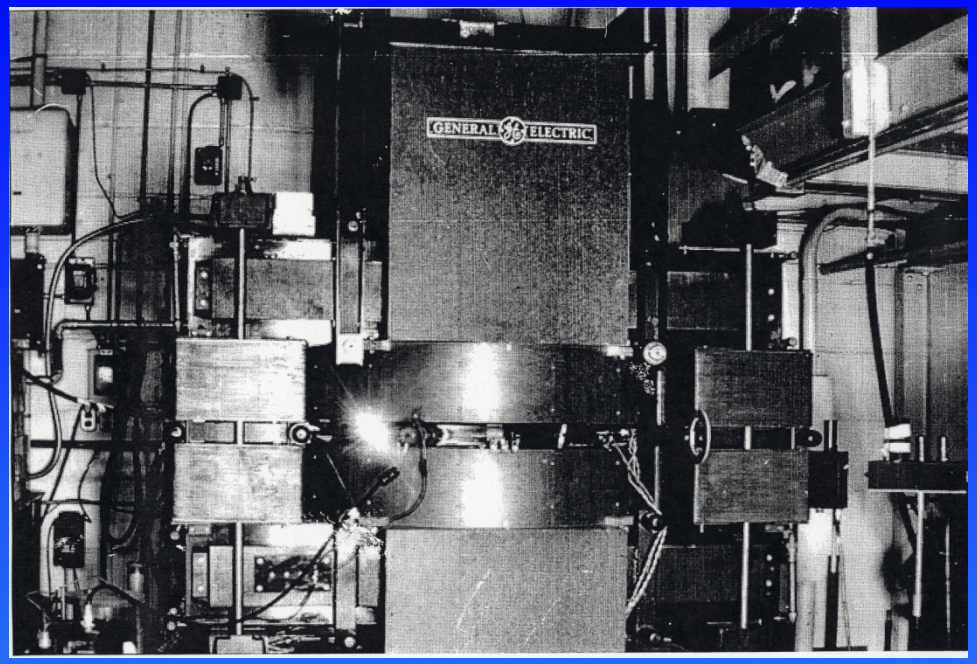
- Brightness = total number of photons
- Brilliance = total number of photons in specific solid angle

High brightness

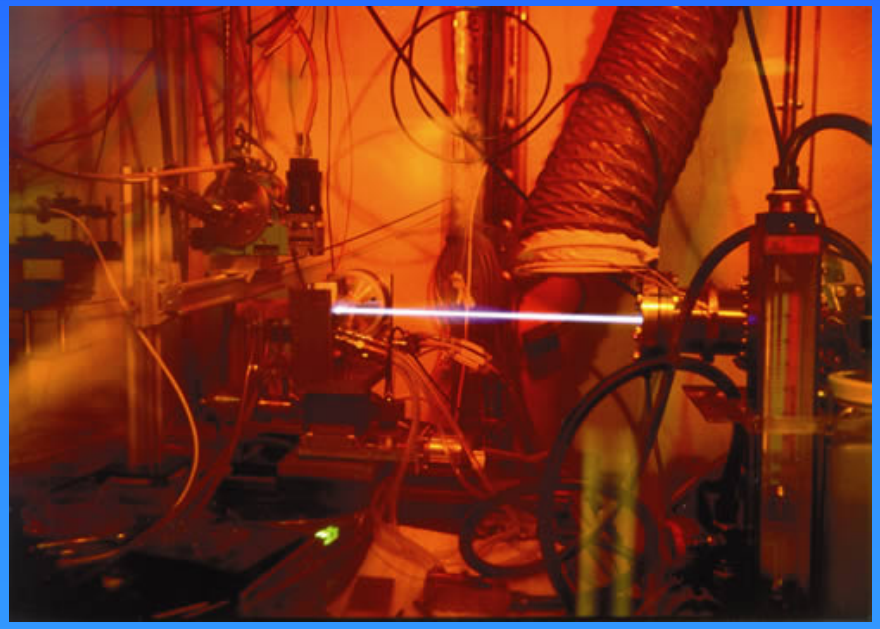
- High flux
- Doesn’t specify how big the sample should be
- Maybe only useful for baking hamburgers

High brilliance

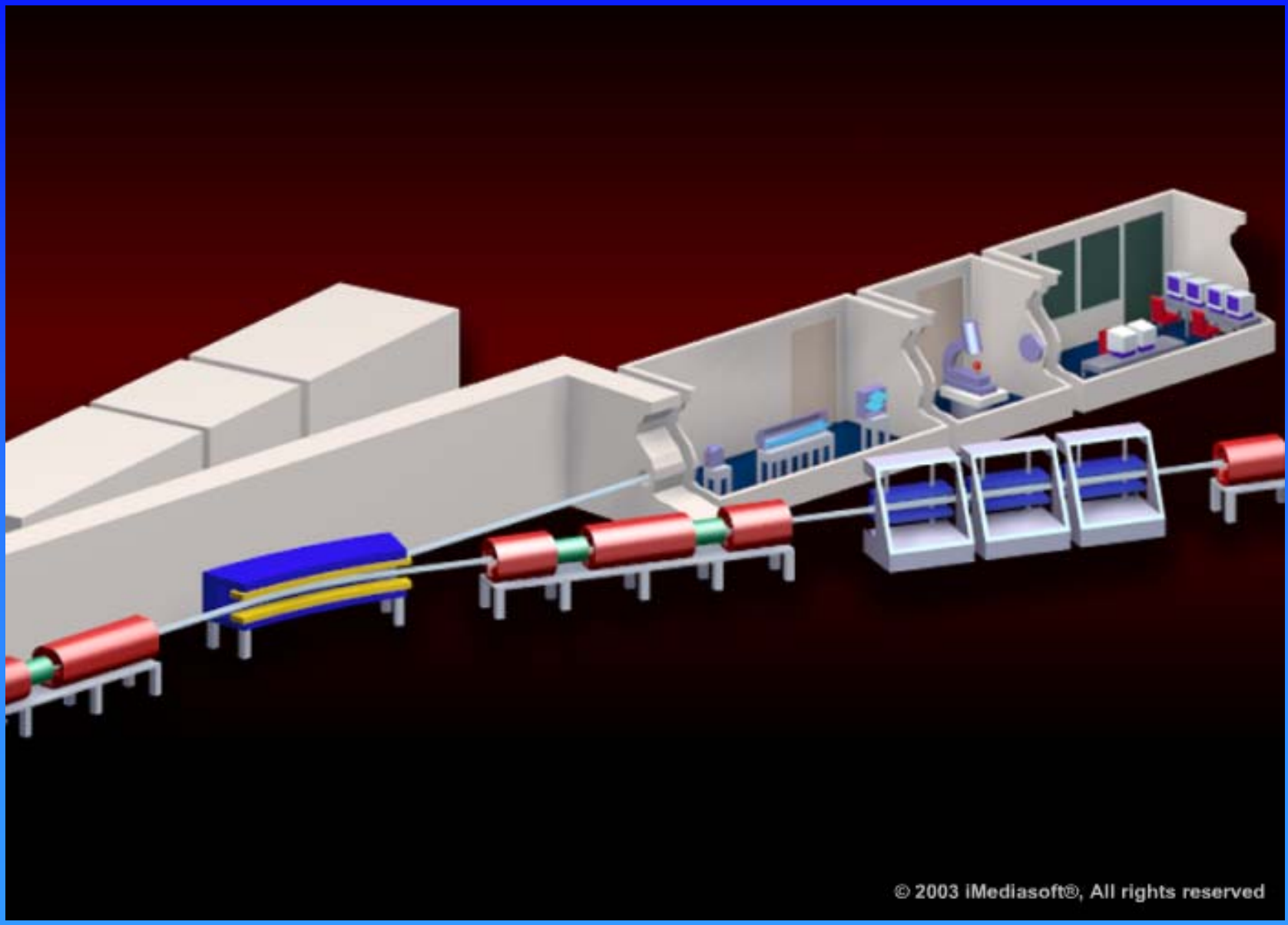
- Large number of photons
- All in a small solid angle
- Suitable to bake hamburgers only very locally



1947
visible light



1980 X-rays
2000 very many X-rays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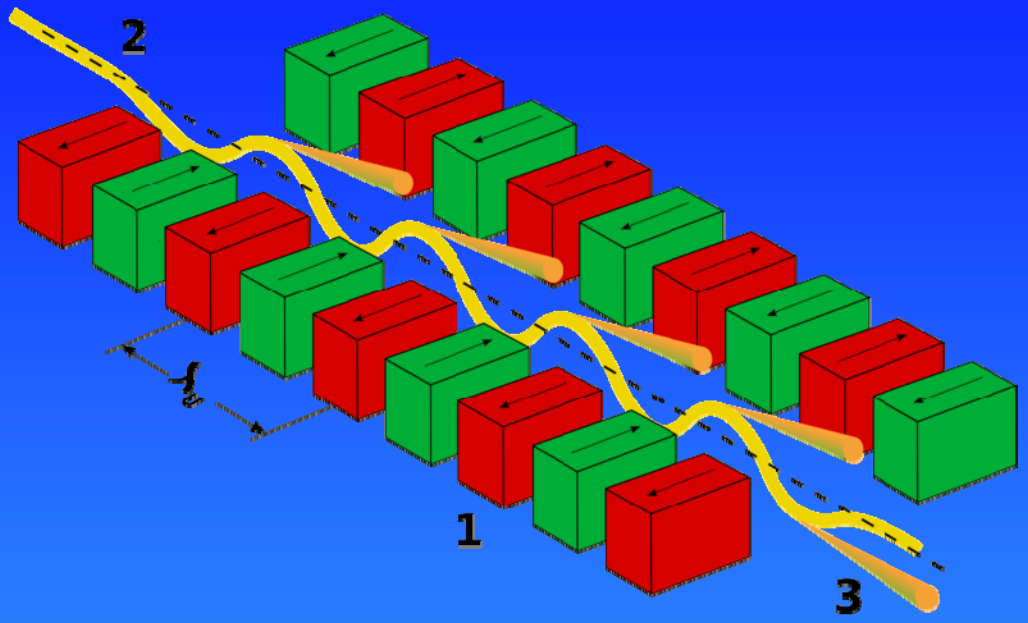
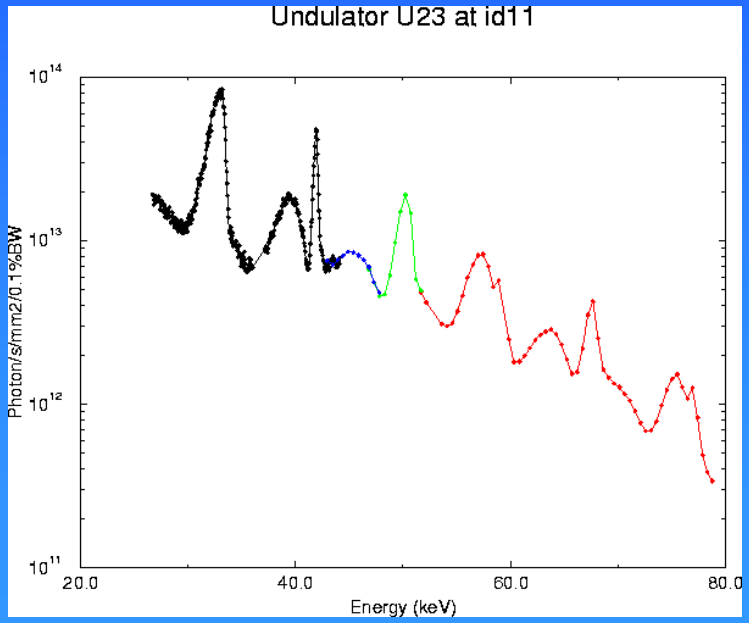
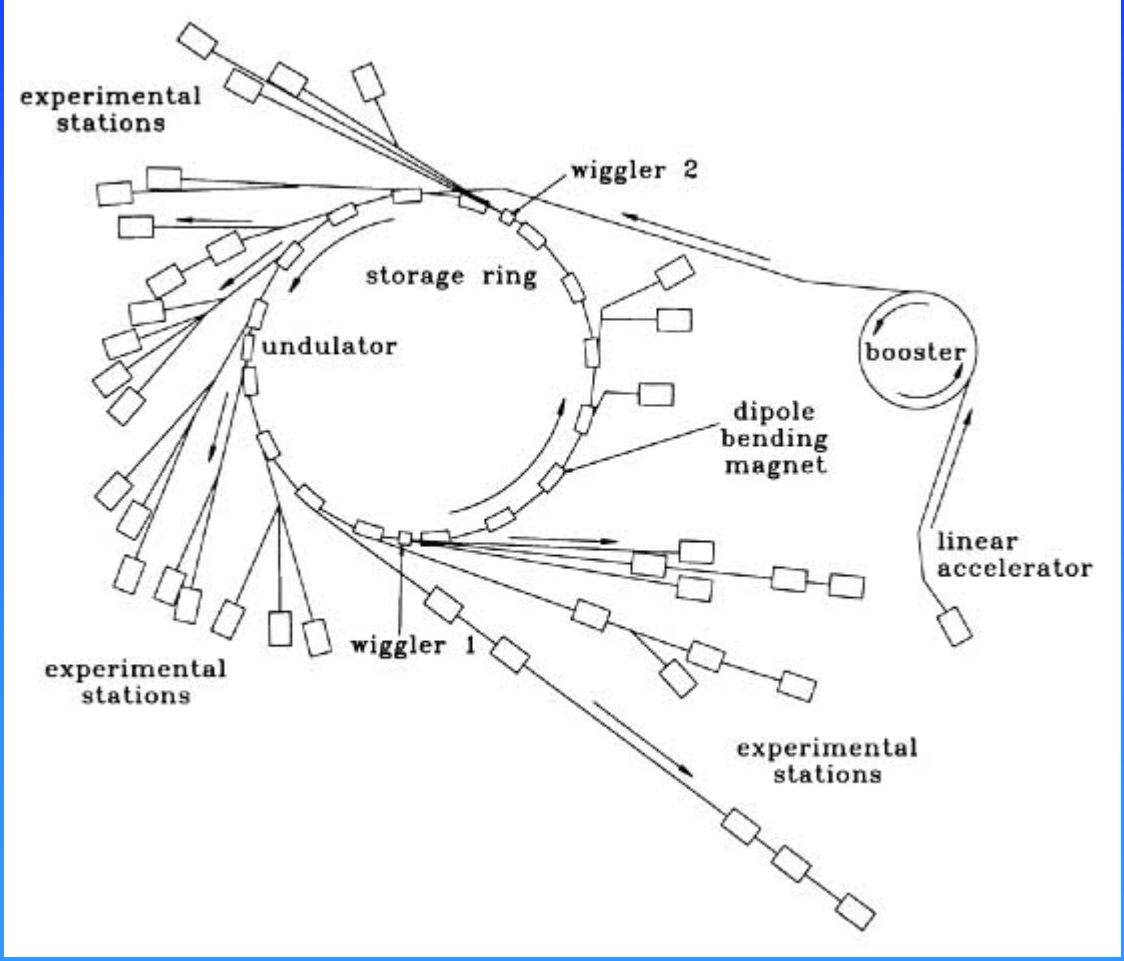
undulators

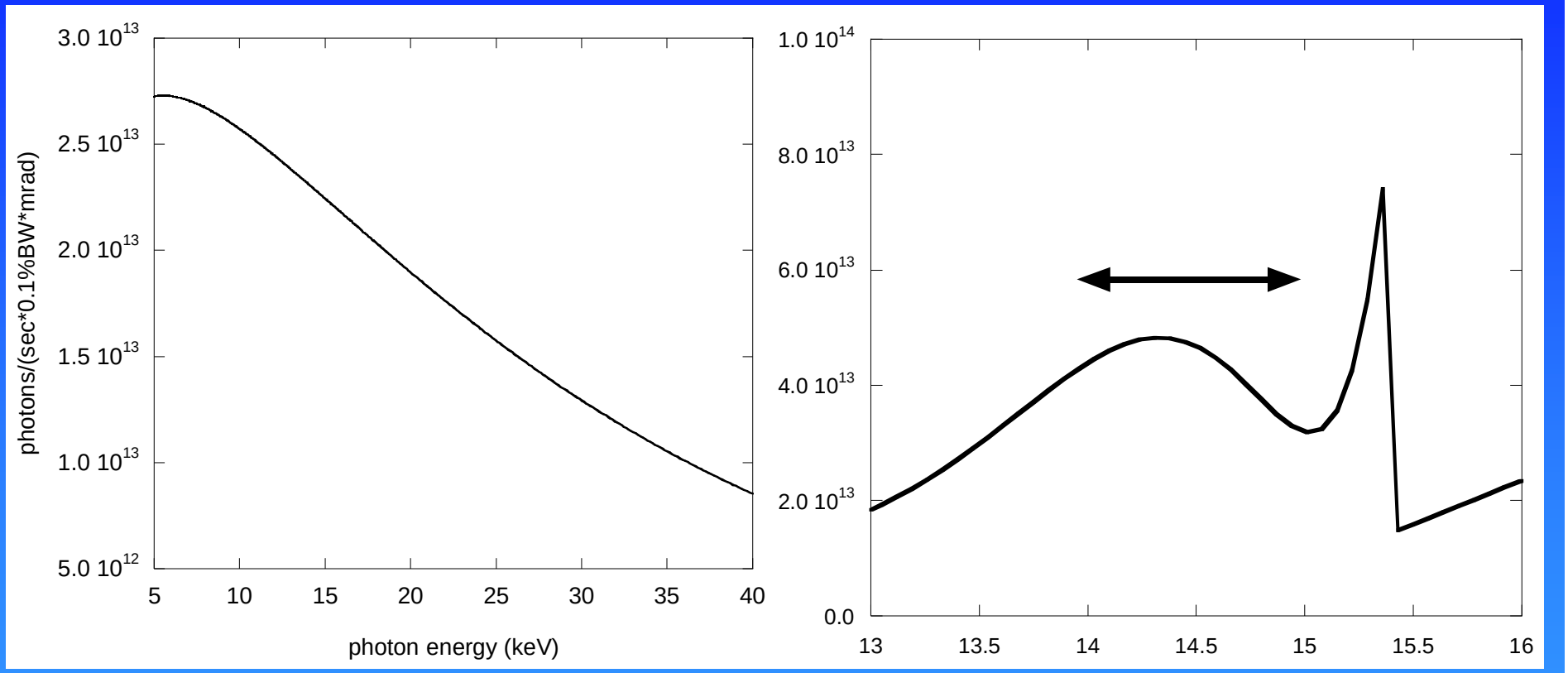


The main points:
-Smaller beamsize
-Higher flux




experimental stations
wiggler 2
storage ring
undulator
booster
dipole bending magnet
linear accelerator
wiggler 1
experimental stations
experimental stations

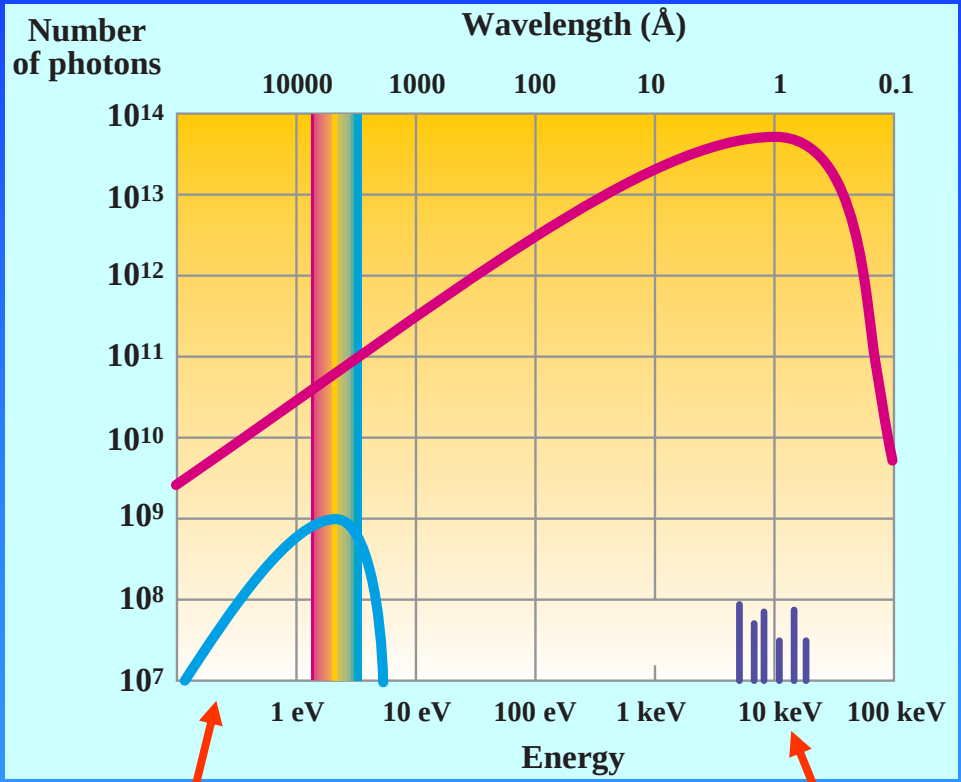
Bending magnet/undulator



Good collimation
High flux
Continuous spectrum

Better collimation
Higher flux
Discontinuous spectrum

What is in the end the advantage of SR?



sunlight

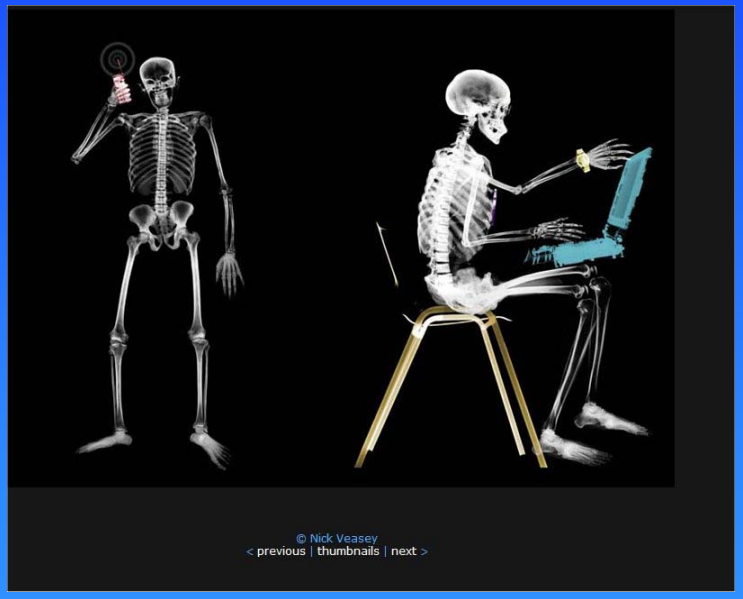
conventional
X-ray generator

- High flux
- Continues spectrum
- Good collimation
- Beams 1 – 300 micron

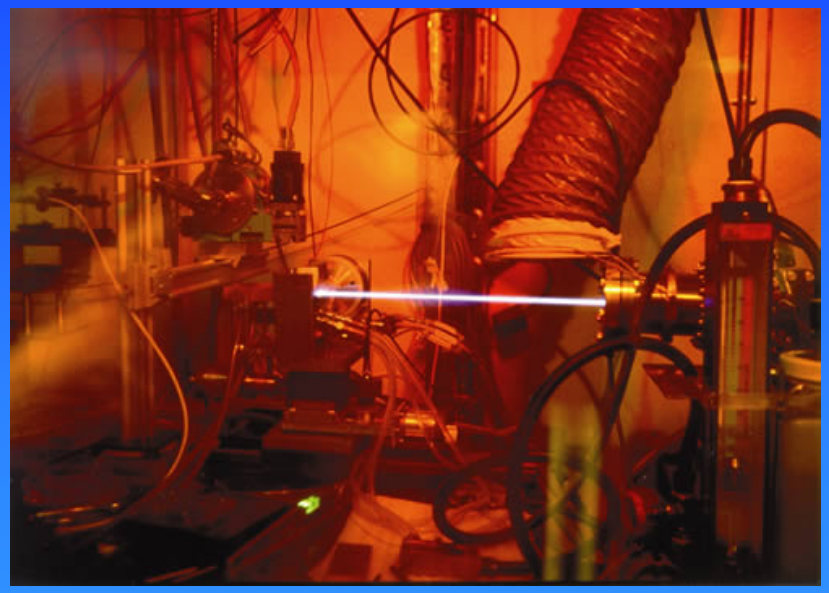
Very high radiation doses

- Standing in front of a bending magnet in operation will slice you in two halves within a second

- The experiment rooms have walls of 12 mm thick lead

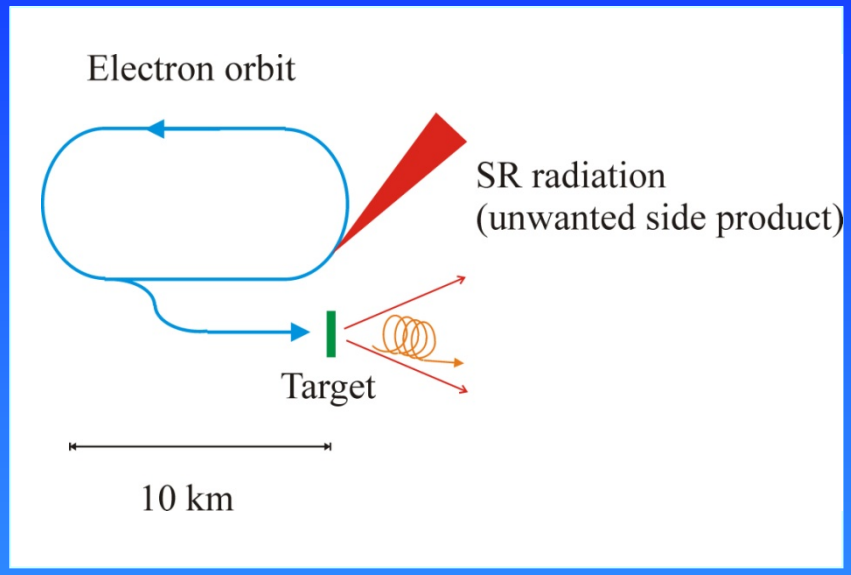


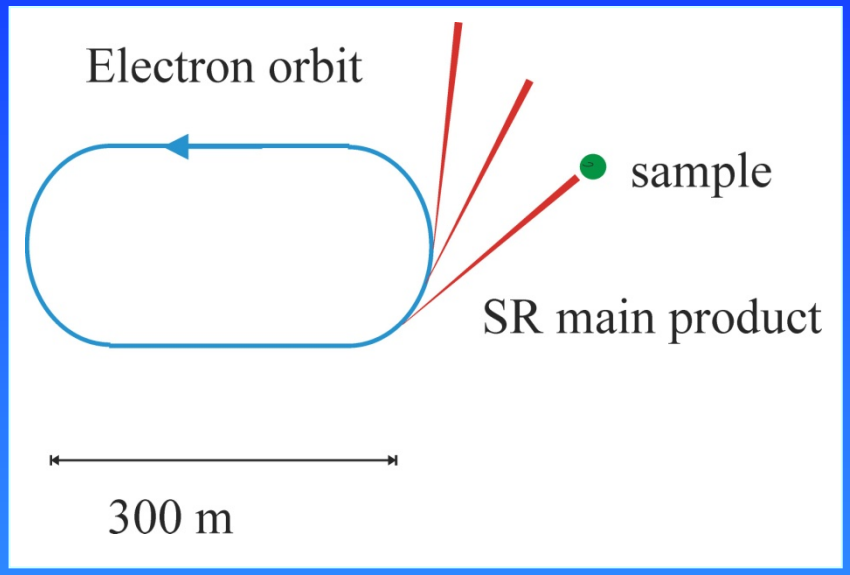
This is what you know



This is what scientist like to use

Geneve vs. Grenoble





Geneve = high energy physics

Bijv. ESRF Grenoble

APS, SRS, NSLS, MAX, ALS

Hasylab, Photon Factory, Elettra, Spring 8

Pohang, Indus, VEPP, Helios 2, Diamond, Soleil etc etc.

If you can read this you don't need reading glasses

Worldwide at present

- 3 high energy machines (ESRF, APS, SPRING8)
- many intermediate energy facilities (Diamond, Soleil, Alba, SLS etc.
- Several low energy machines (Bessy, ALS etc.)

- In total 30 – 40 institutes


SOR-Ring


DUBBLE

The start of synchrotron radiation user facilities

Daresbury also birth place of Lewis Carrol

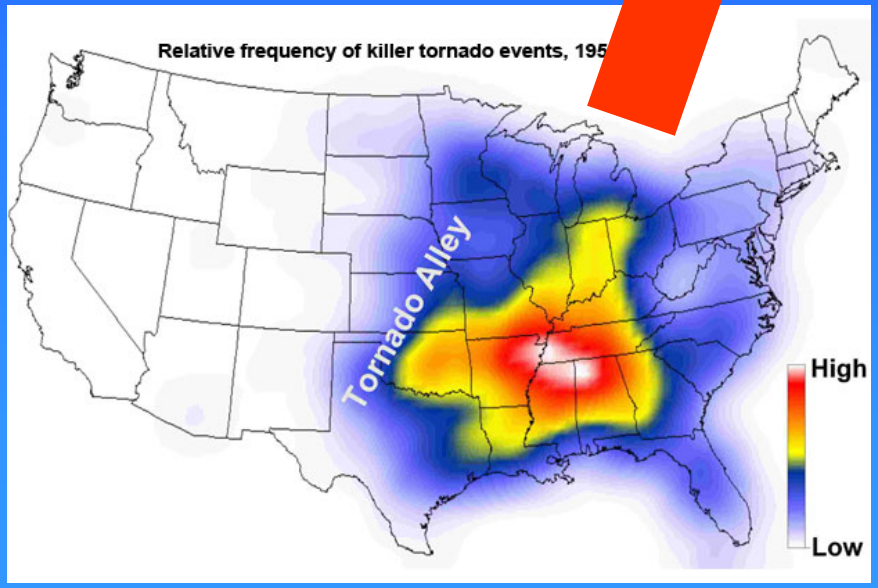
Daresbury lab in Cheshire

- About 40 years ago this was the first lab to be dedicated to SR production and run as a user facility

- Stable geological environment required
  - Large machines
  - Small beams
- Small amount of site vibrations
- Stable power supply

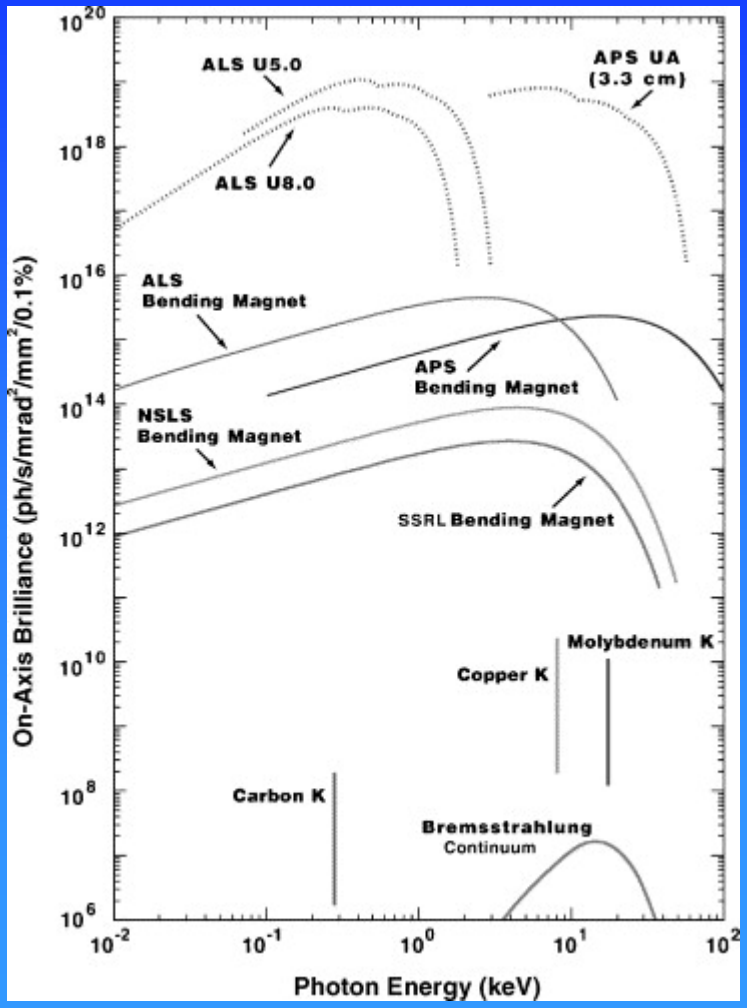
Stupid places to build a synchrotron 1

Stupid places to build a synchrotron 2



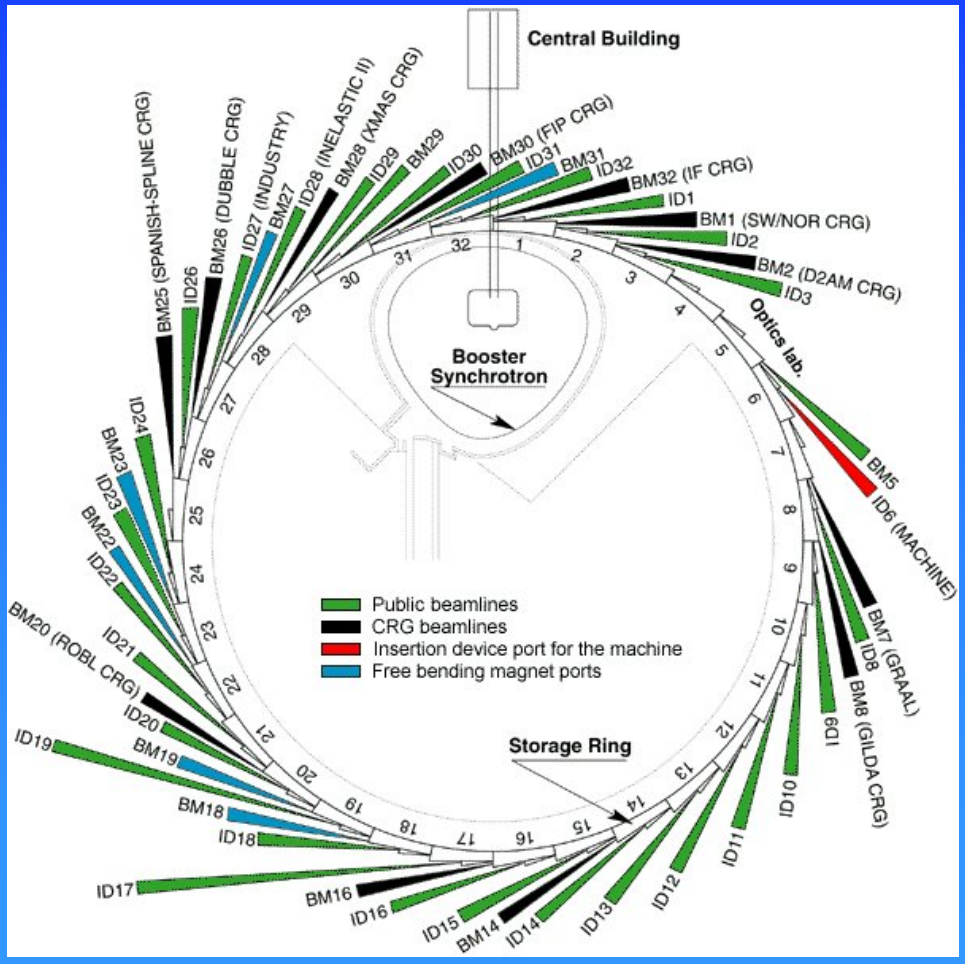
Stupid places to build a synchrotron 3

Are all these SR sources the same?

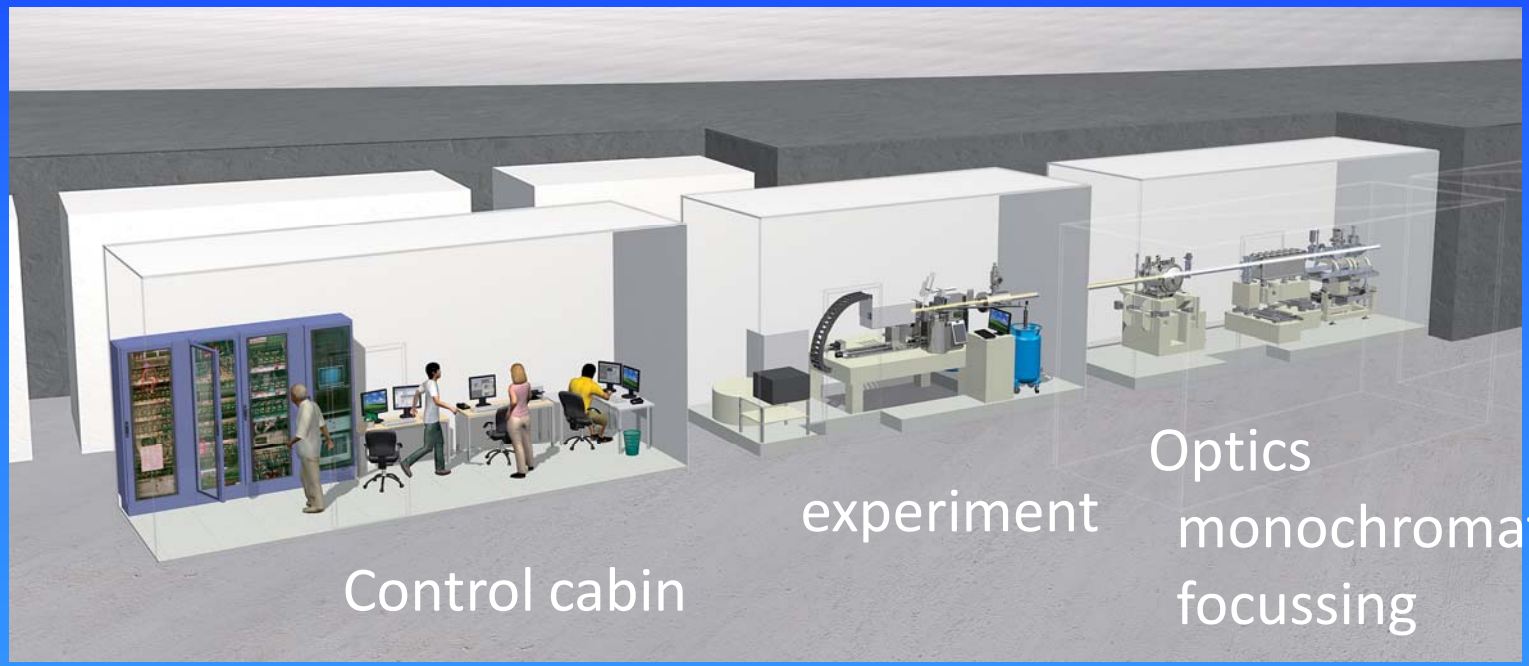


- Spectrum depends on
  - electron energy
  - Electron beam size
  - Bending magnet field
  - Ring current

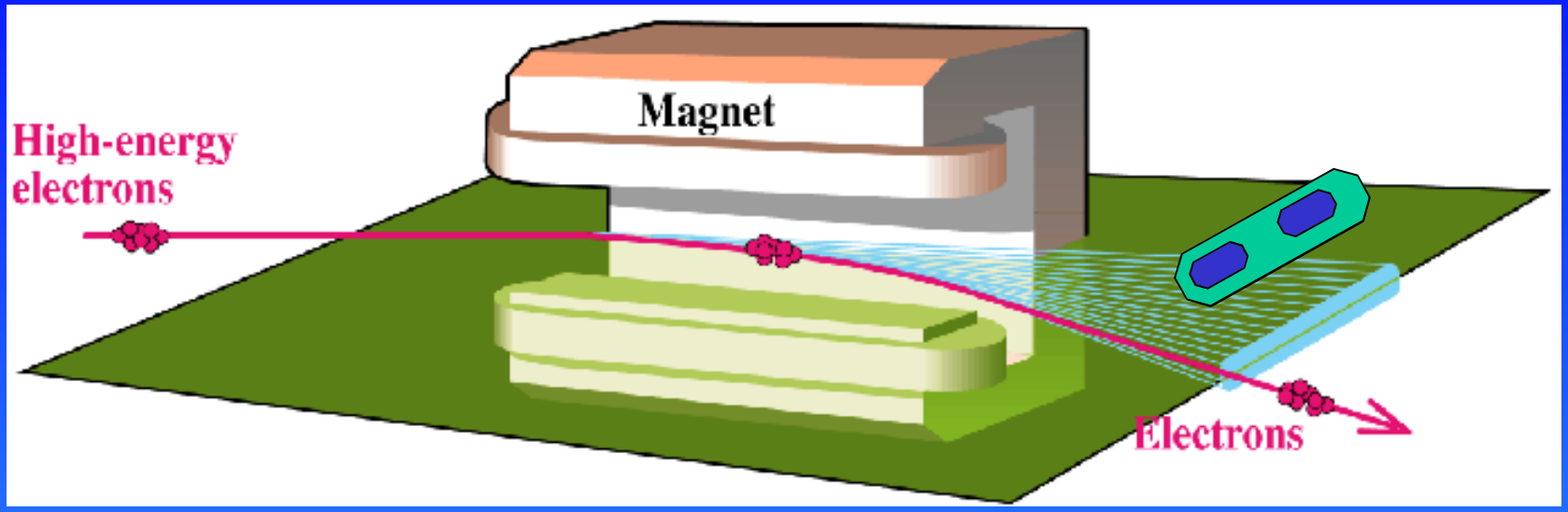
Why so many beam lines?



Scheme beam line



storage ring


Magnet
High-energy
electrons
Electrons

A beam line

SAXS
Control cabin

EXAFS
Experiments hutch

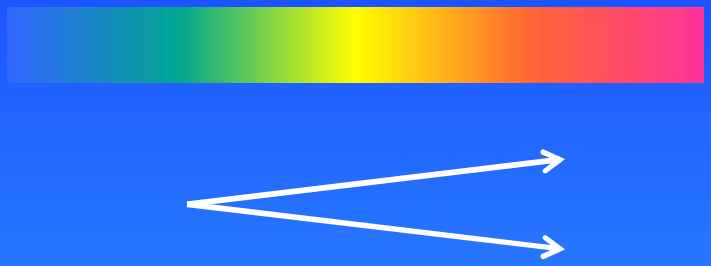
SAXS
Experiments hutch

EXAFS
Control cabin

Optics hutch
'massaging the raw beam into a useable form'

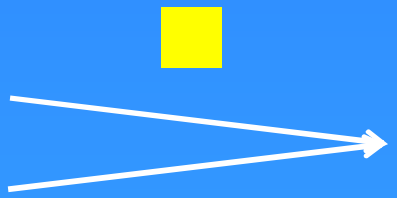
When X-ray beam comes out of the machine:

- Polychromatic
- Slightly divergent

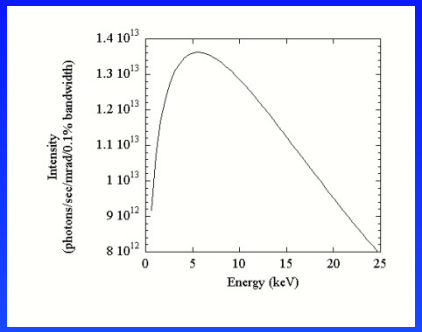


Most times we want:

- Monochromatic
- Focussing

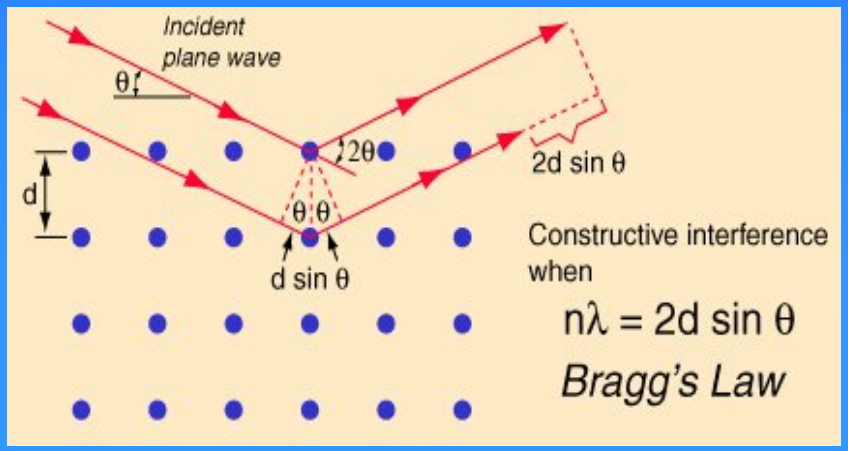


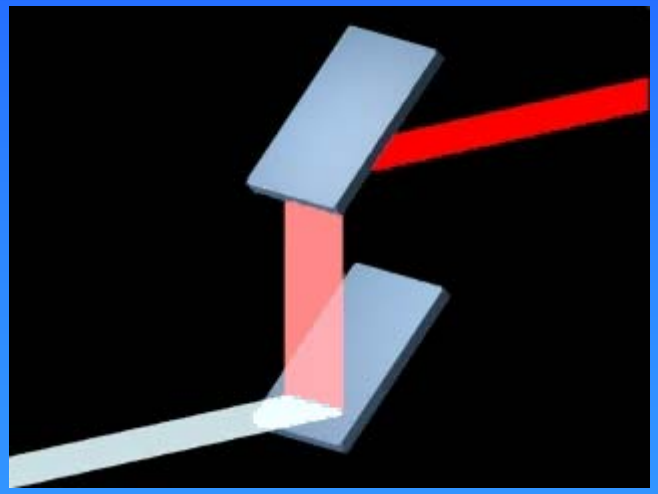
Monochromator



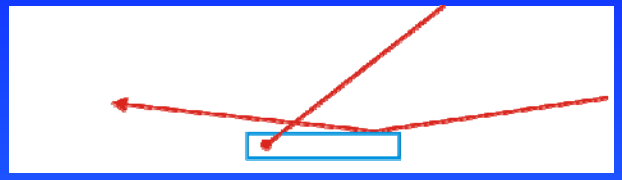
In general made of Si

The angle of incidence determines the transmitted wavelength/energy

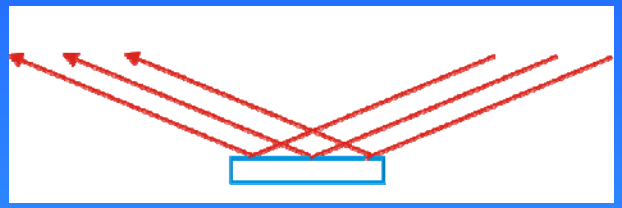




Reflective optics

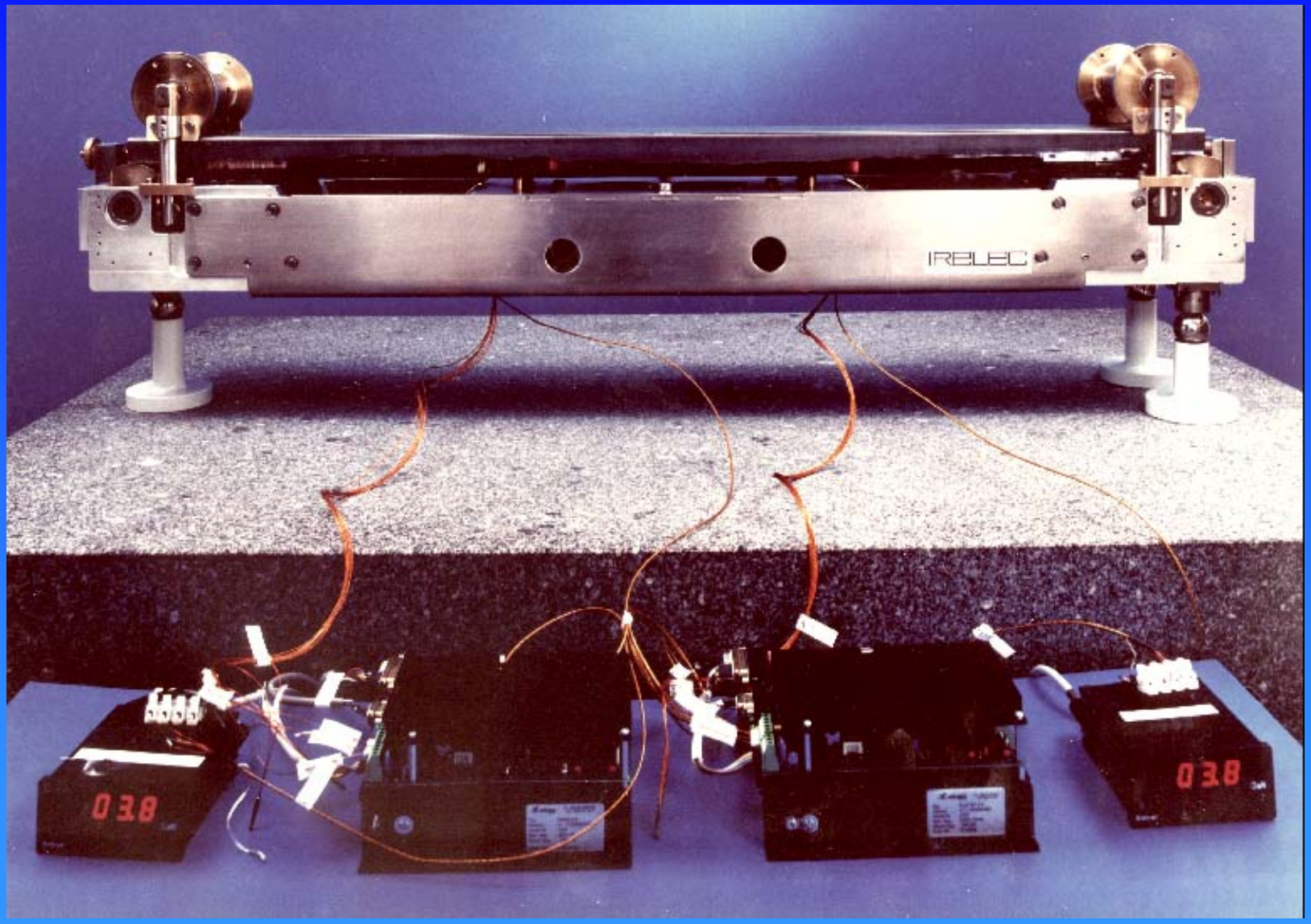


Grazing incidence required
Angle ≈ 1-3 mrad



Very smooth surface
Roughness max few Ångstrom

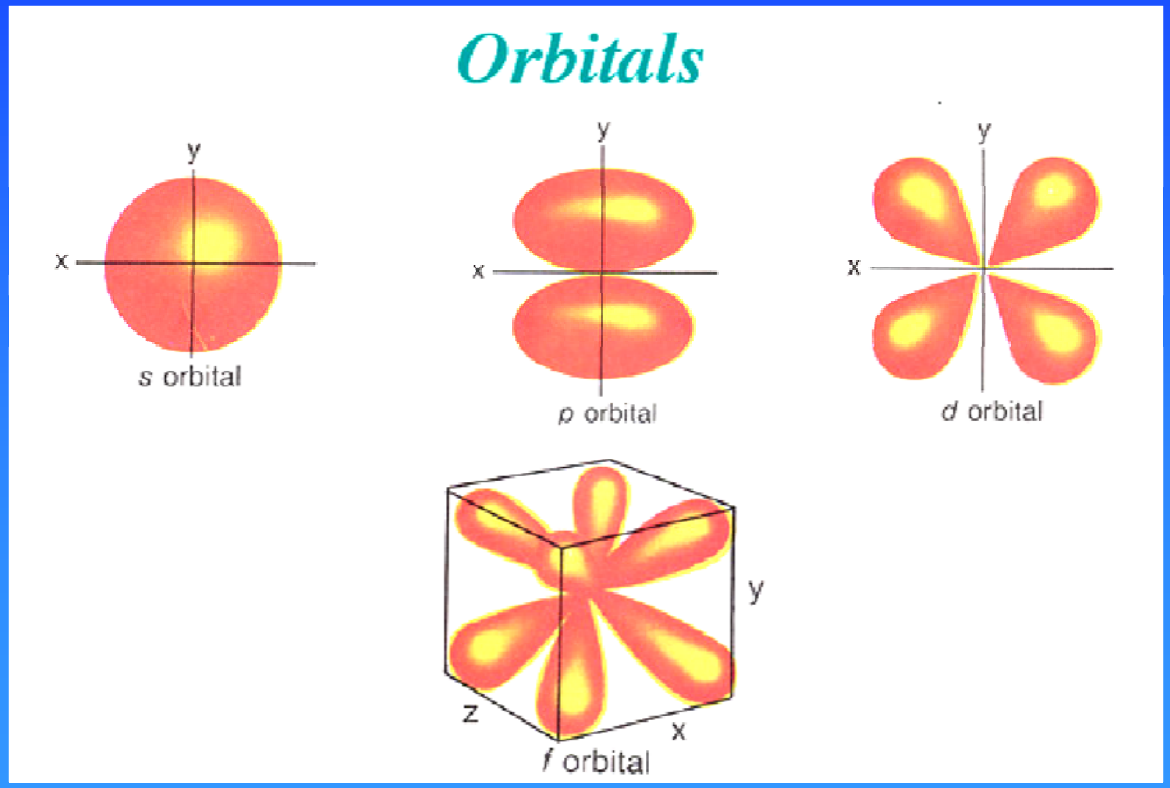
Bending for focusing
Bending radii several kilometer


IRELEC

Beamline

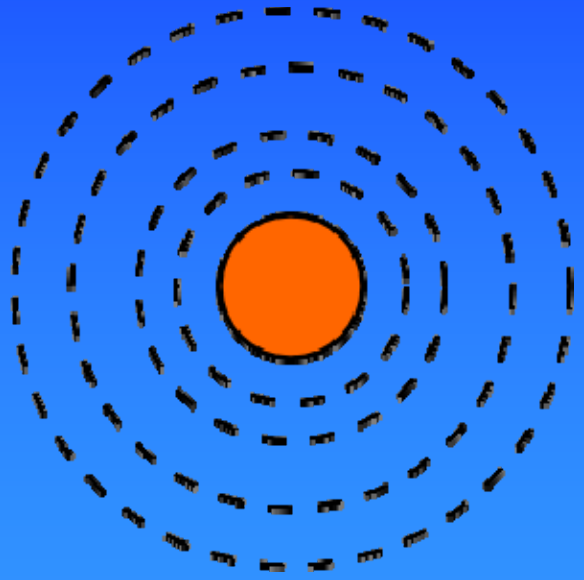
- Optical elements
  - Monochromator
  - Mirrors
- Product
  - Monochromatic beam $\Delta\lambda/\lambda \approx 10^{-4}$
  - Very well collimated beam (1 -300 micron)
  - Focussed beam
  - (rarely ‘white’ beam)

X-ray spectroscopy



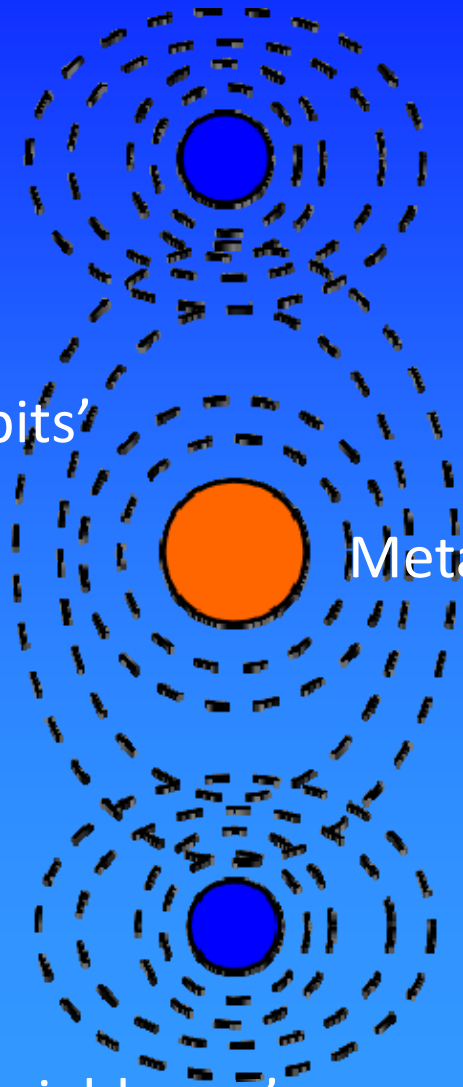
X-ray spectroscopy

‘electron orbits’



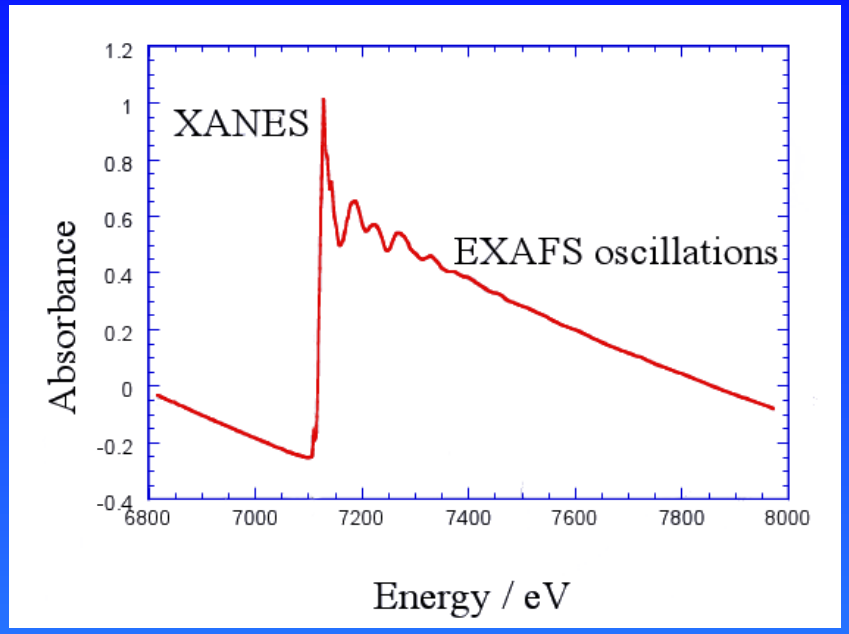
Metal atom

deformed
‘electron orbits’



Metal atom

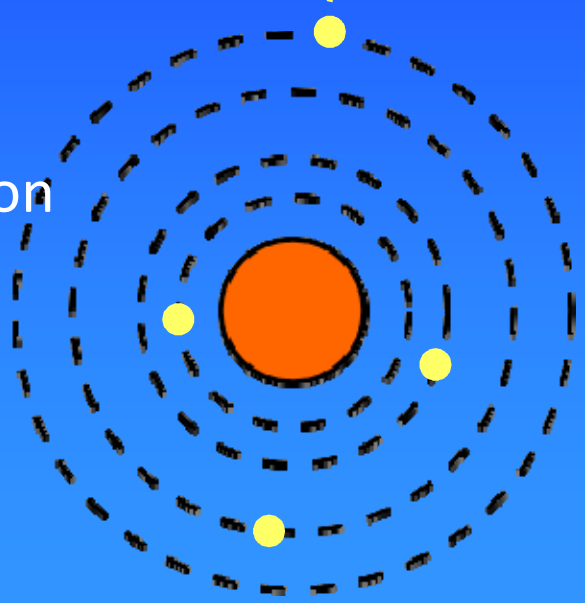
‘neighbours’



ionisation

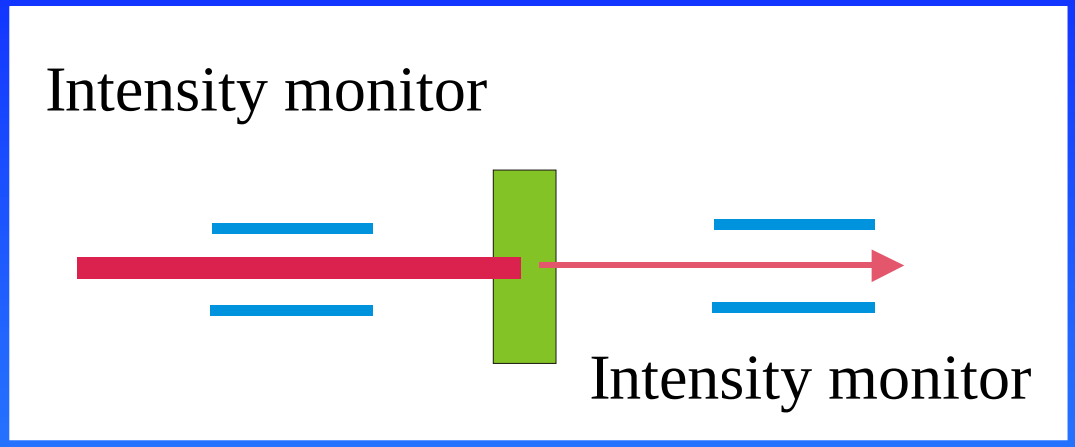
Röntgen photon

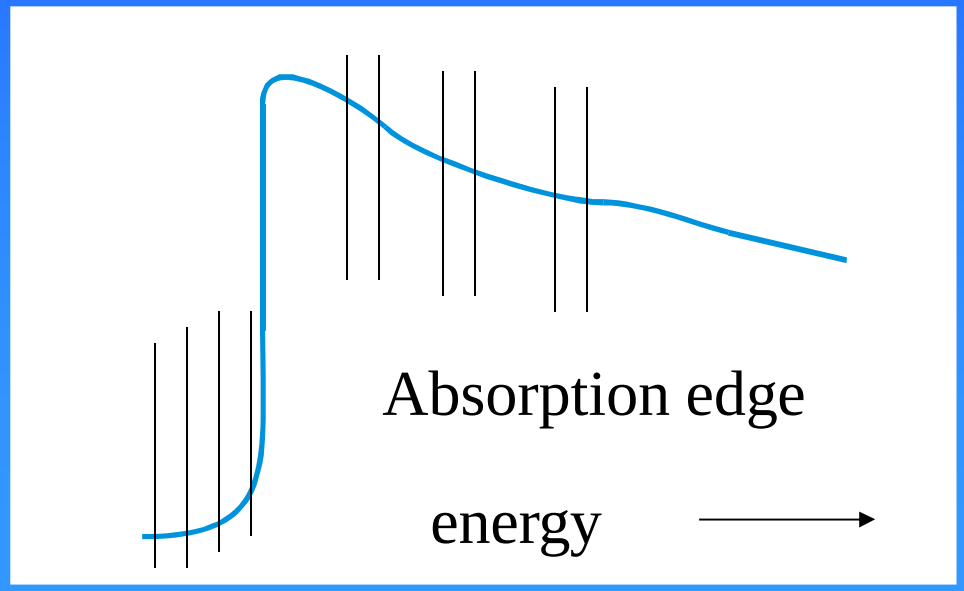
absorbed



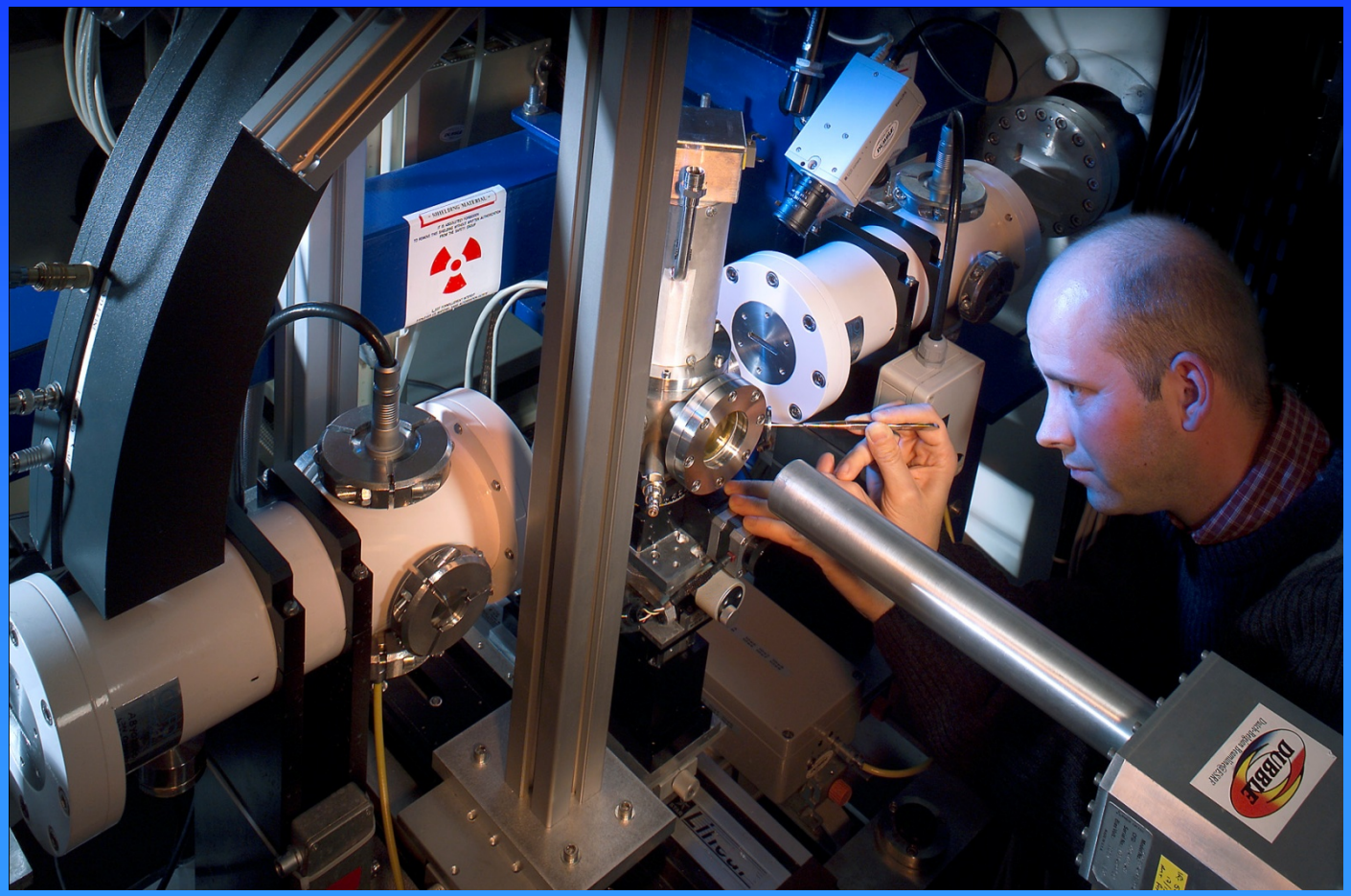
$$\frac{I_t}{I_0}(E)$$

EXAFS

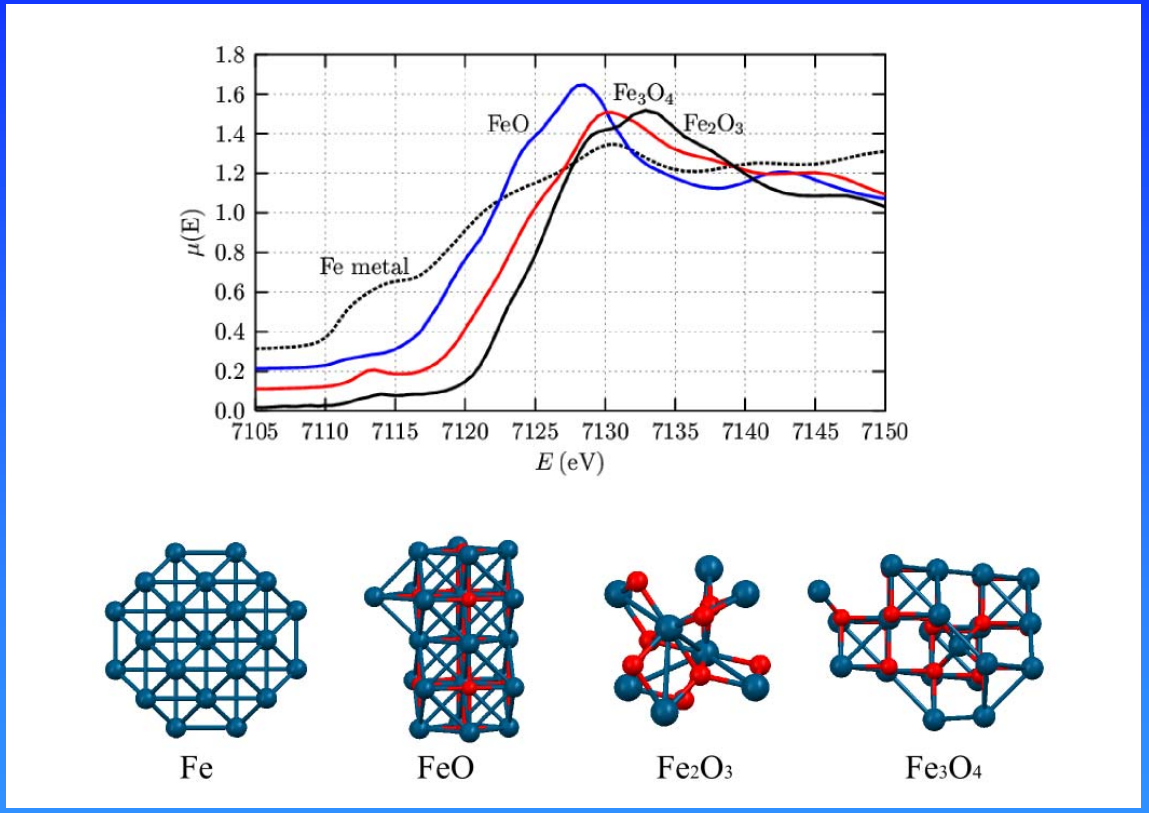




$$\frac{I_t}{I_0}(E)$$


SHIELDING MATERIAL
DUBBLE

Difference in surroundings of metal atom; difference in absorption spectrum



Multidisciplinary

catalysis

Hydrogen storage

liquid metals

pharmaceuticals

Environmental pollution

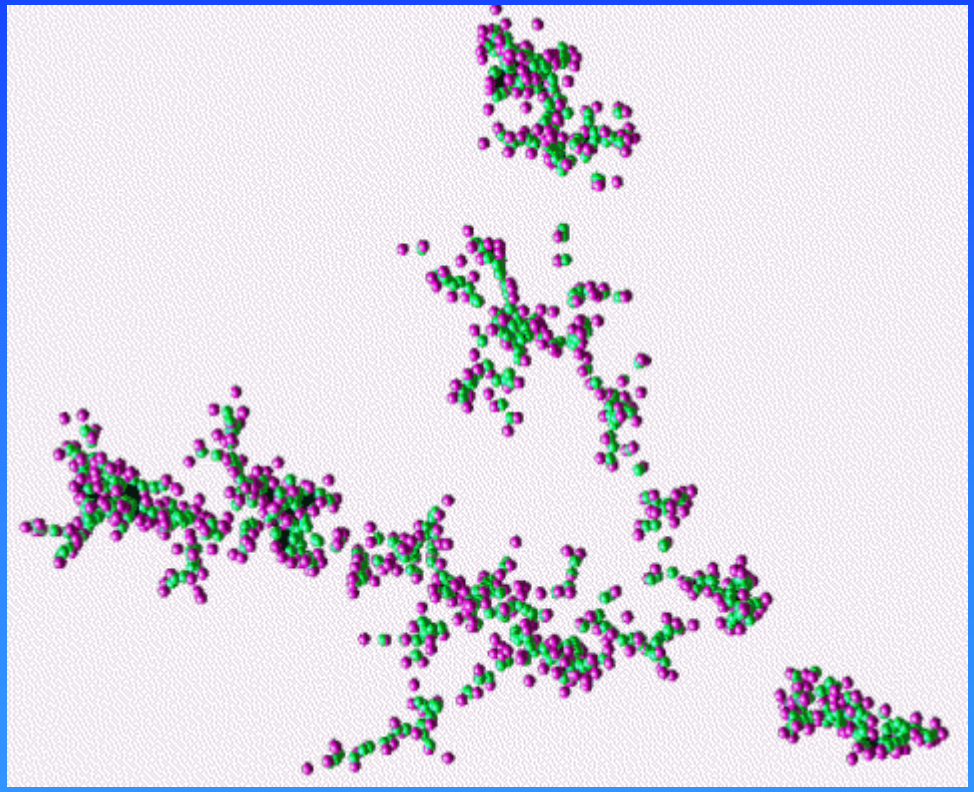
electro chemistry
cultural heritage

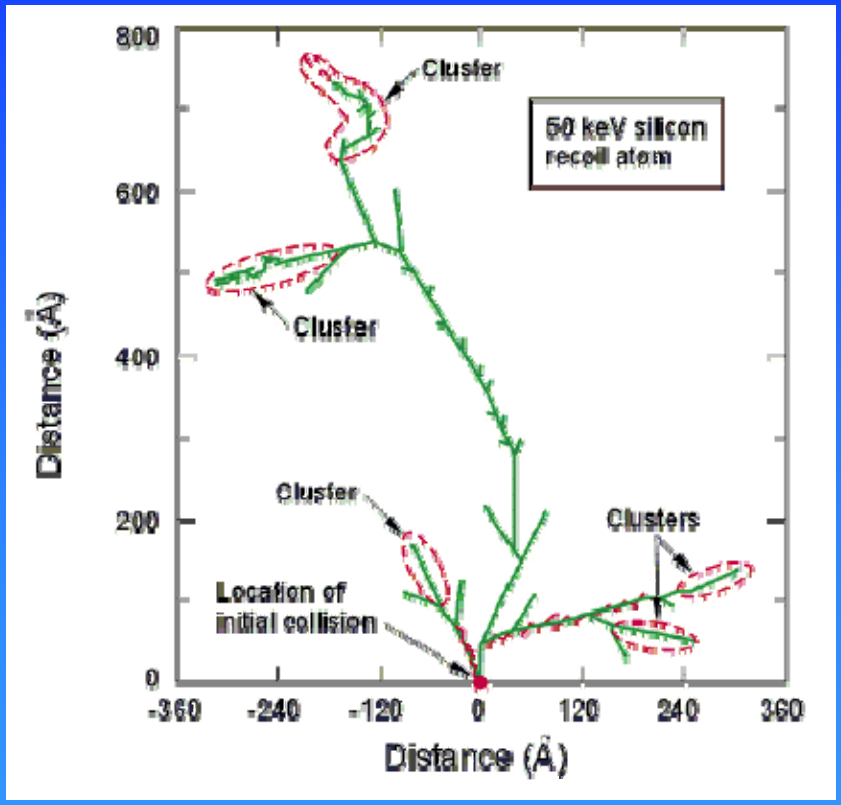
Etc., etc., etc….

How can this now be used for radiation damage studies?

- It gives information about local environment of probe atoms (< 1 nm)
- It does not provide information about longe range damage (> 1 nm)

For instance damage clusters





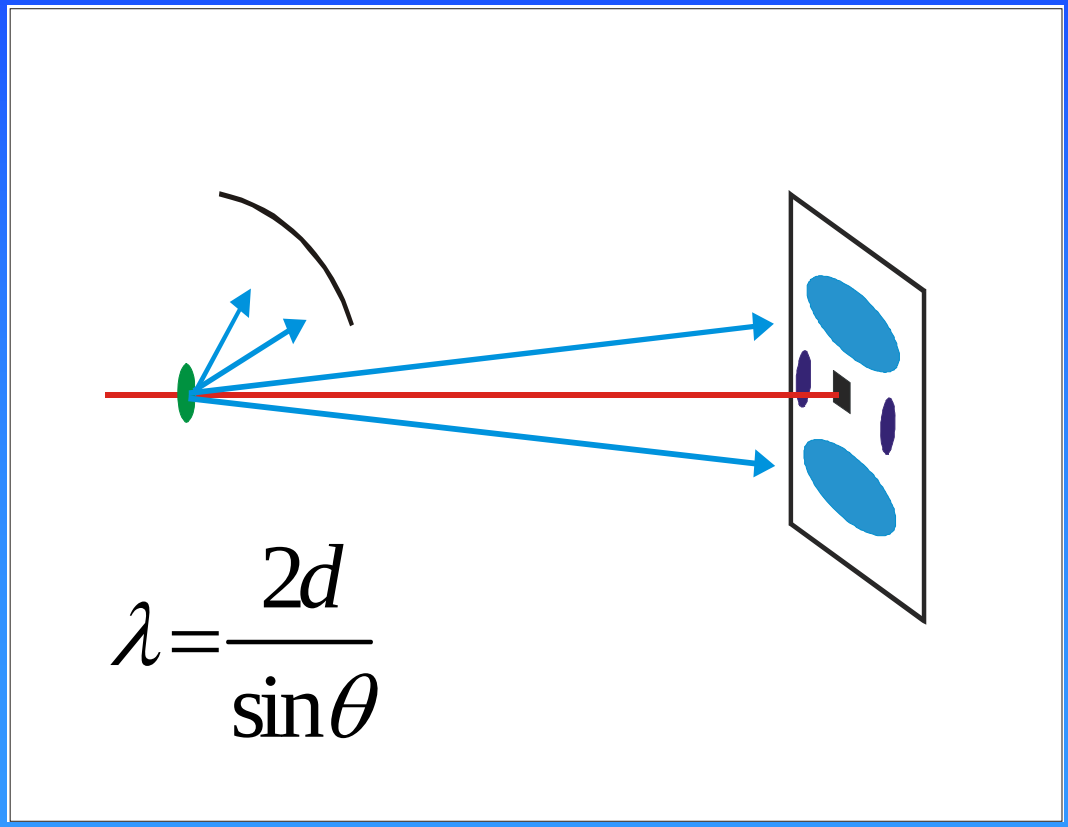
XAFS

- XANES
  - Information about first surrounding shell of probe atom
- EXAFS
  - Information on other shells

SAXS and WAXS

Small and Wide Angle X-ray Scattering

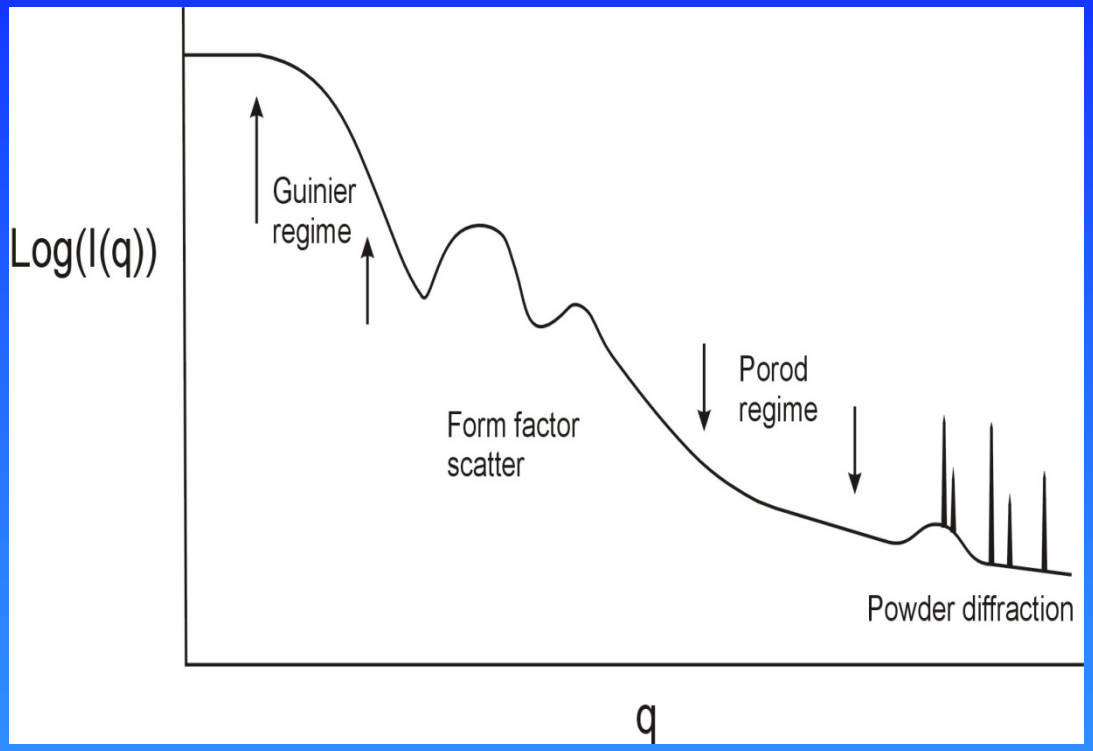
d small, θ large



$$\lambda = \frac{2d}{\sin\theta}$$

q small, θ large

SAXS/WAXS



500 nm 0.2 nm

1 limit $q \rightarrow 0$
electron density contrast
density fluctuations
molecular weights

2 Guinier range
particle size
interparticle scattering

3 particle shape
large scale structures

4 Porod range
particle surface
Surface/volume

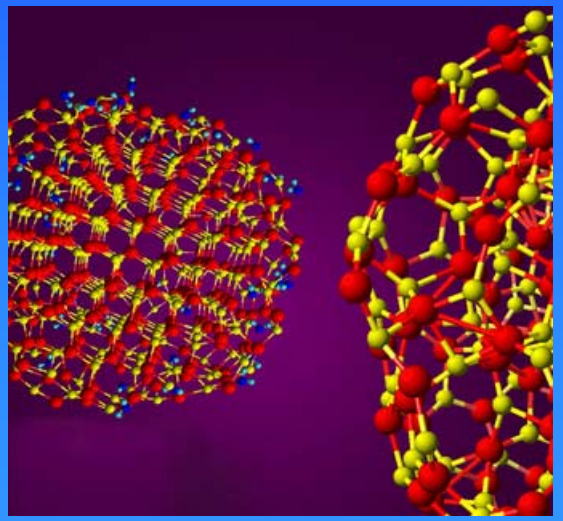
5 Intermolecular/atomic ordering

X-ray scattering and diffraction

- Combined SAXS-WAXS experiments
- WAXS crystalline structure
- Small angle: shape and size of clumps of atoms

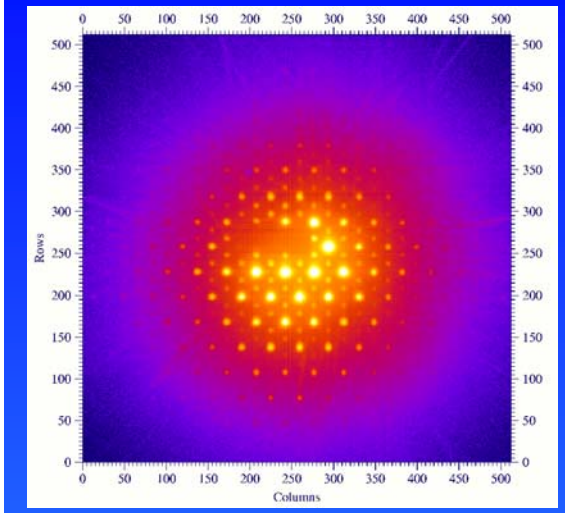
- SR not only static
  also time-resolved

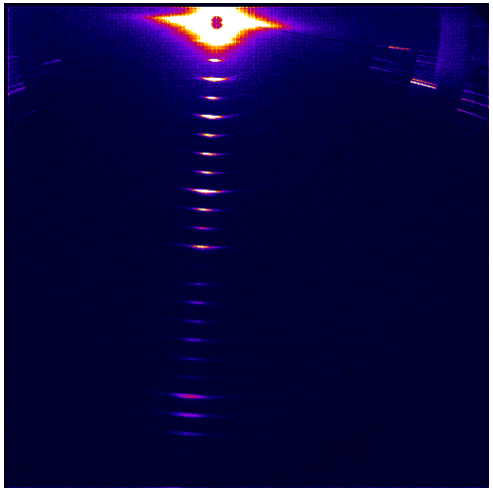
- 0.4 – 200 nm ‘visible’

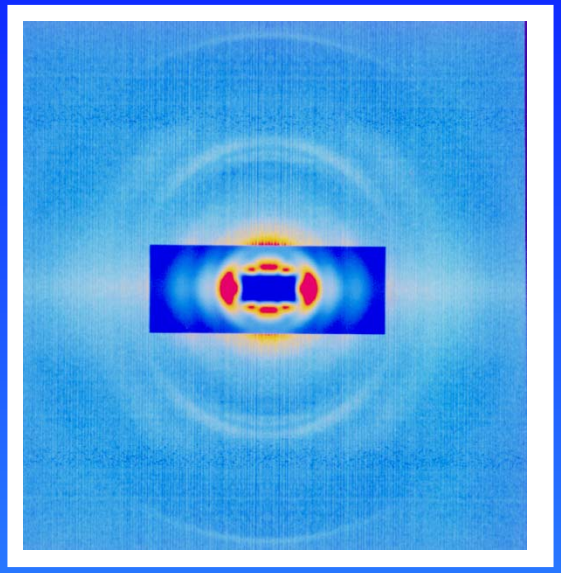


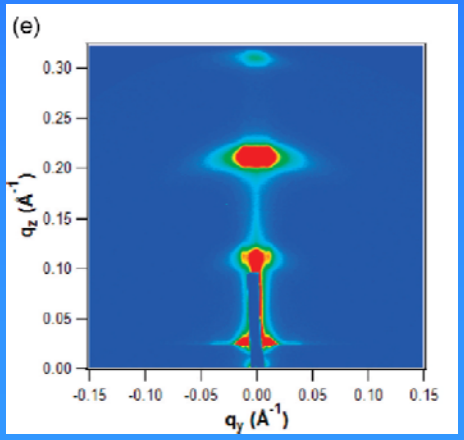
Scattering/diffraction patterns

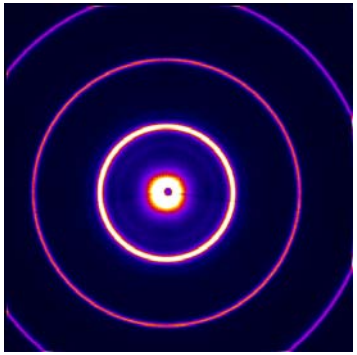
diffractiepatronen

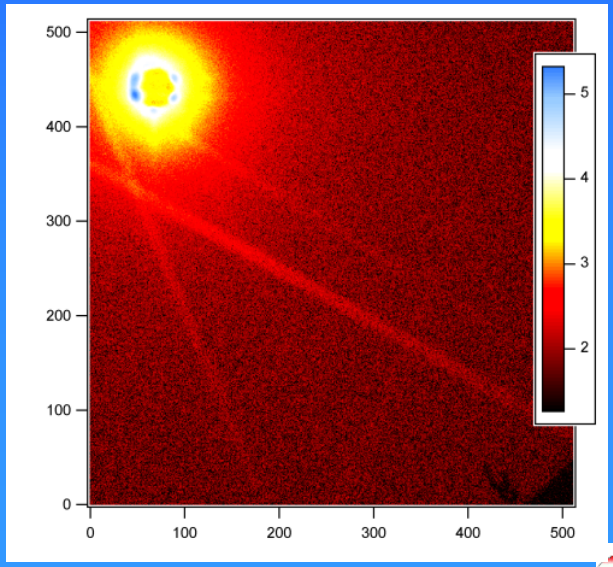




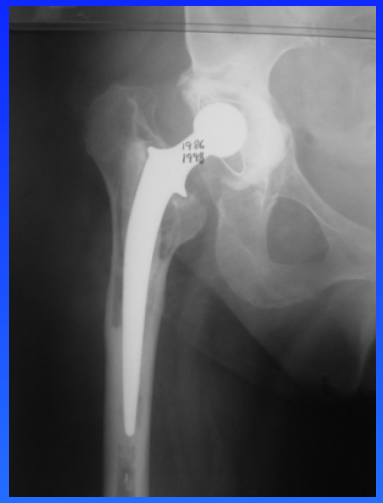






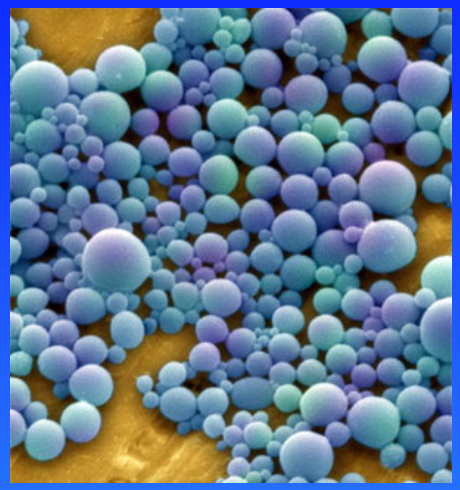


Multidisciplinary applications



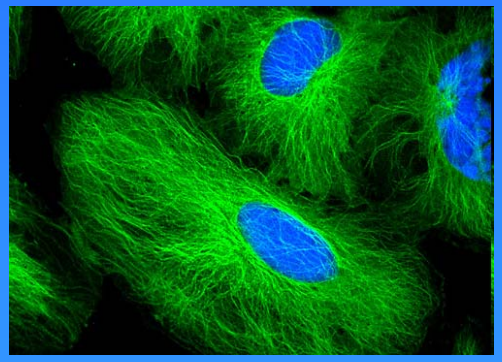
hip replacements

polymer fibers



nano technology

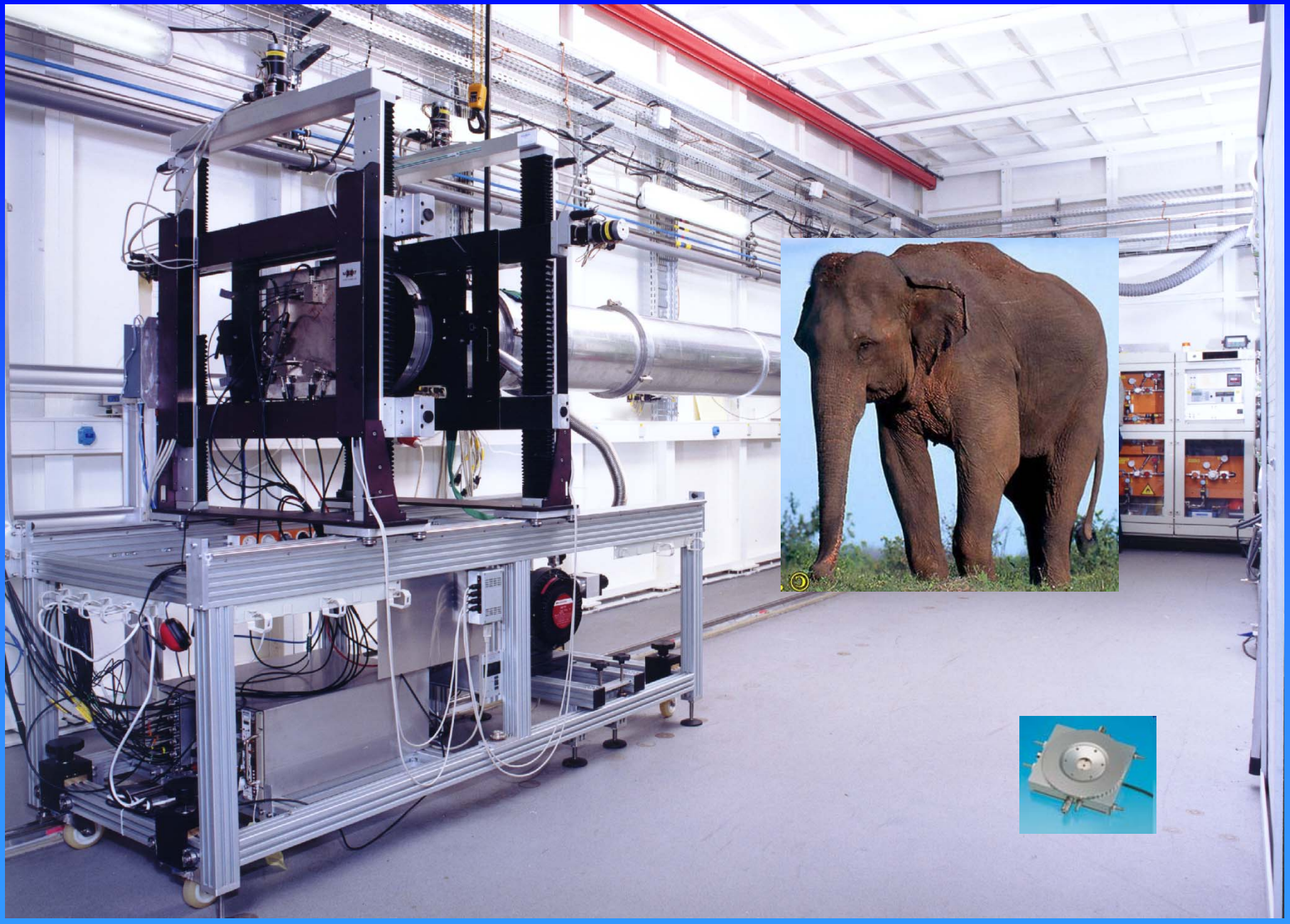
Unwashed Eskimo hair



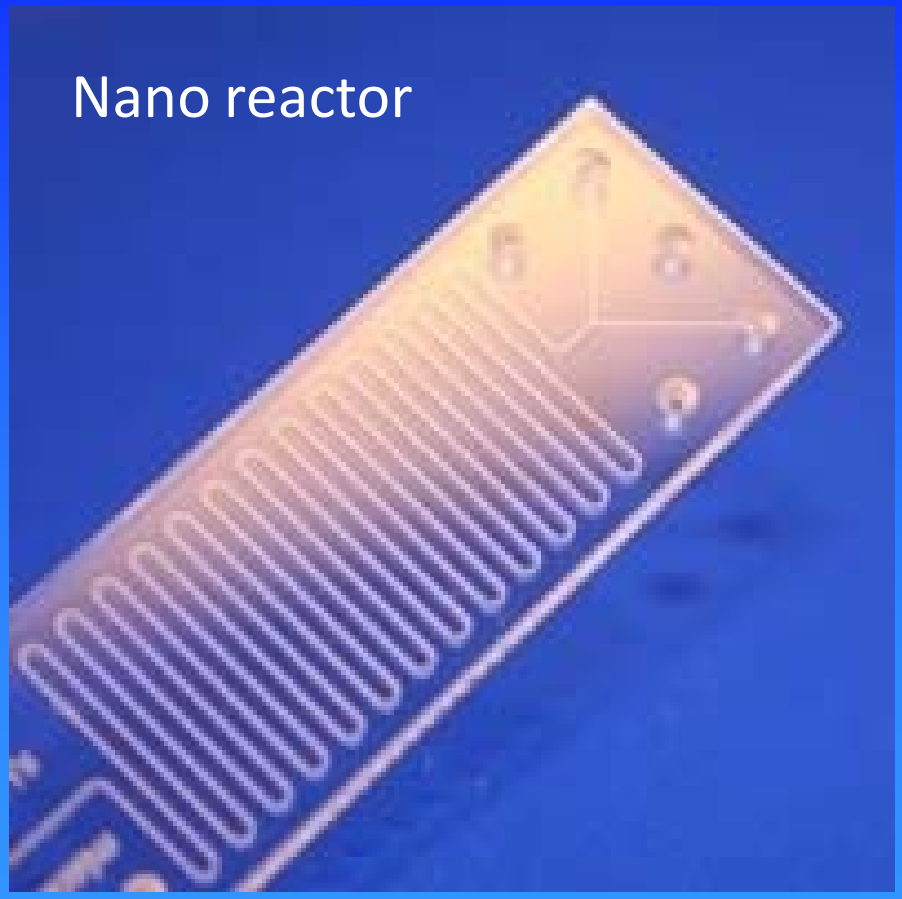
tubulin, cell division

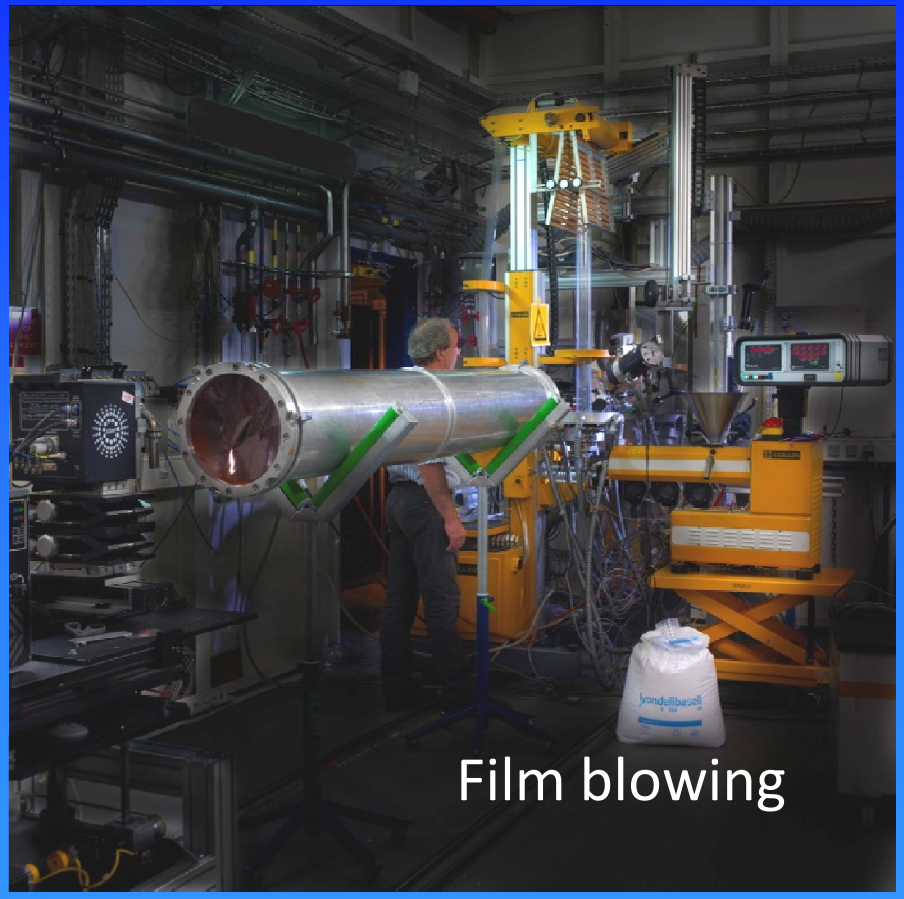
Etc., etc., etc….

Car exhaust
Soot of diesel



Sample holders





Beam sizes from microns to millimeters

What can we do with this in framework of radiation damage?

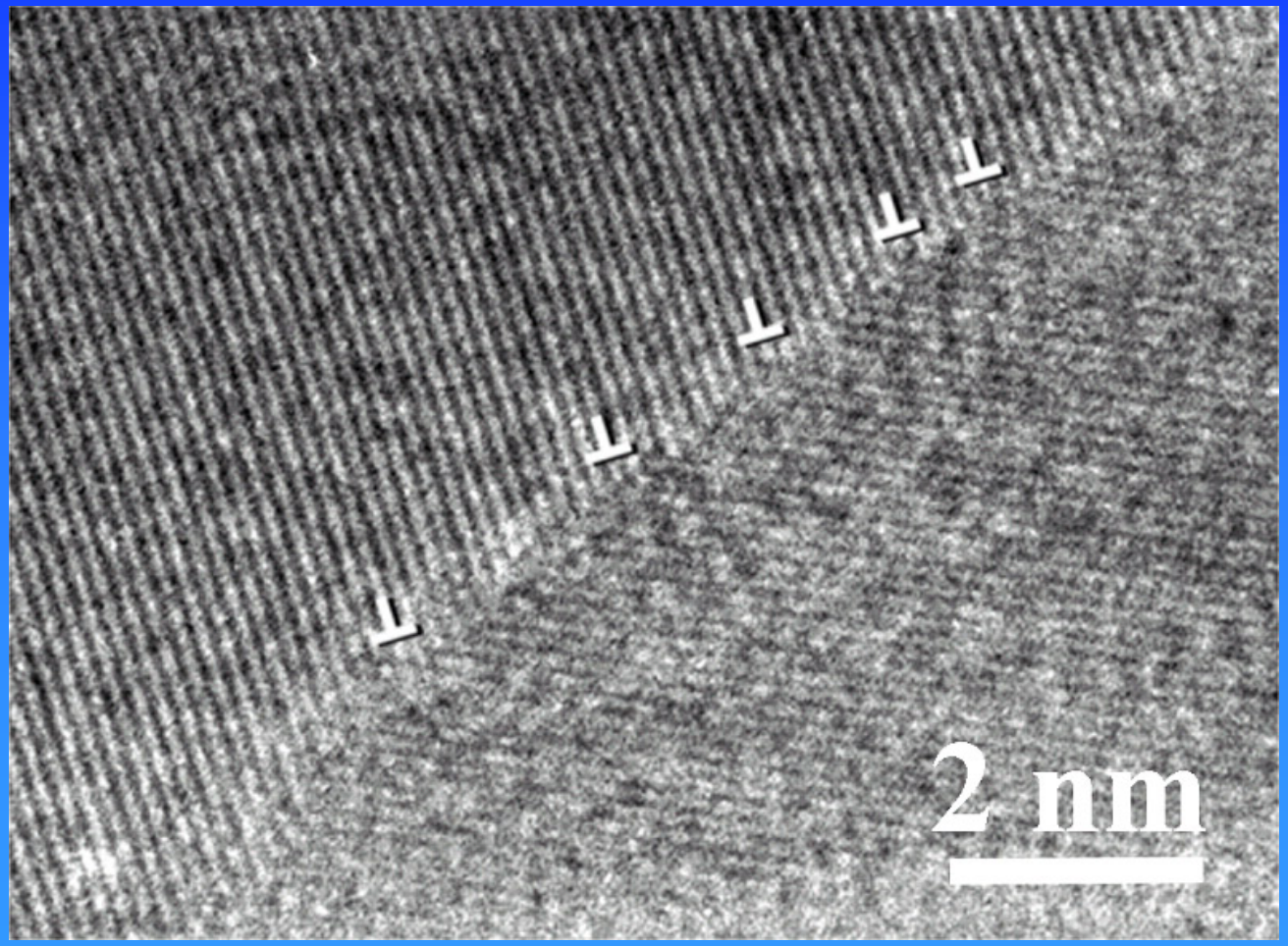
- Long range effects (cracks, clusters etc)
- If a lot of damage WAXS can give structural information
- Important that it is statistically averaged over ‘large’ area
- Therefore complementary to electron microscopy

Information

- Longe range order effects (1 nm – 200 nm)
- Short range order (disruptions to crystalline lattice)

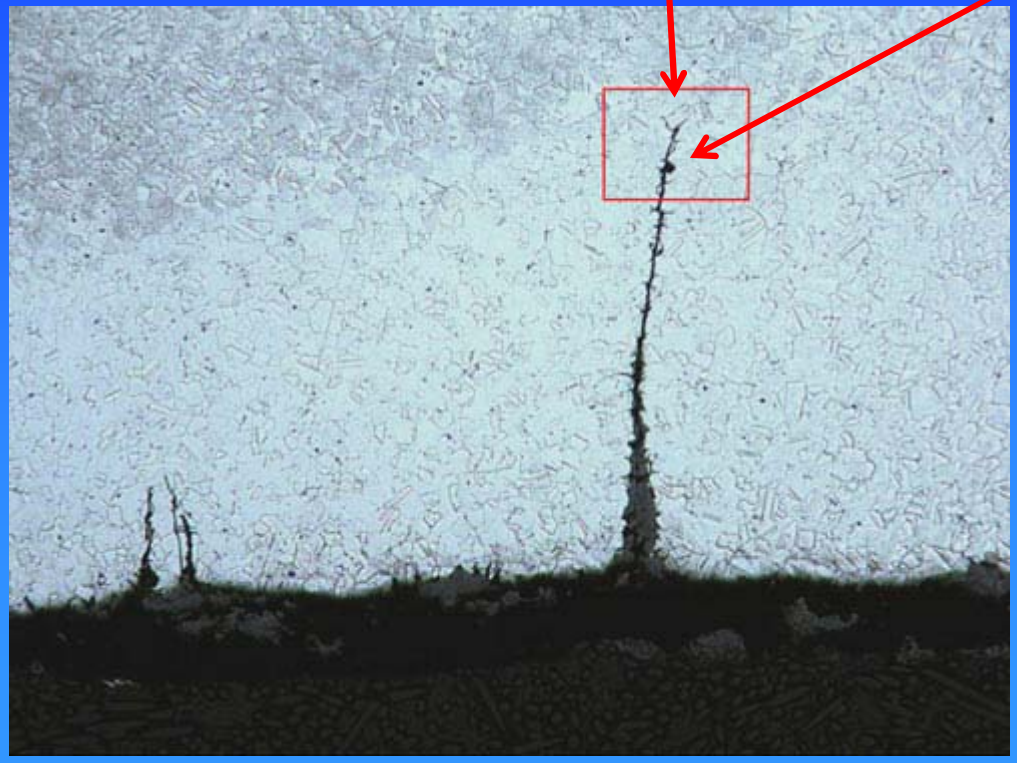
- Required is a rather large number of defects
- One obtains a statistical average

Complementary to TEM

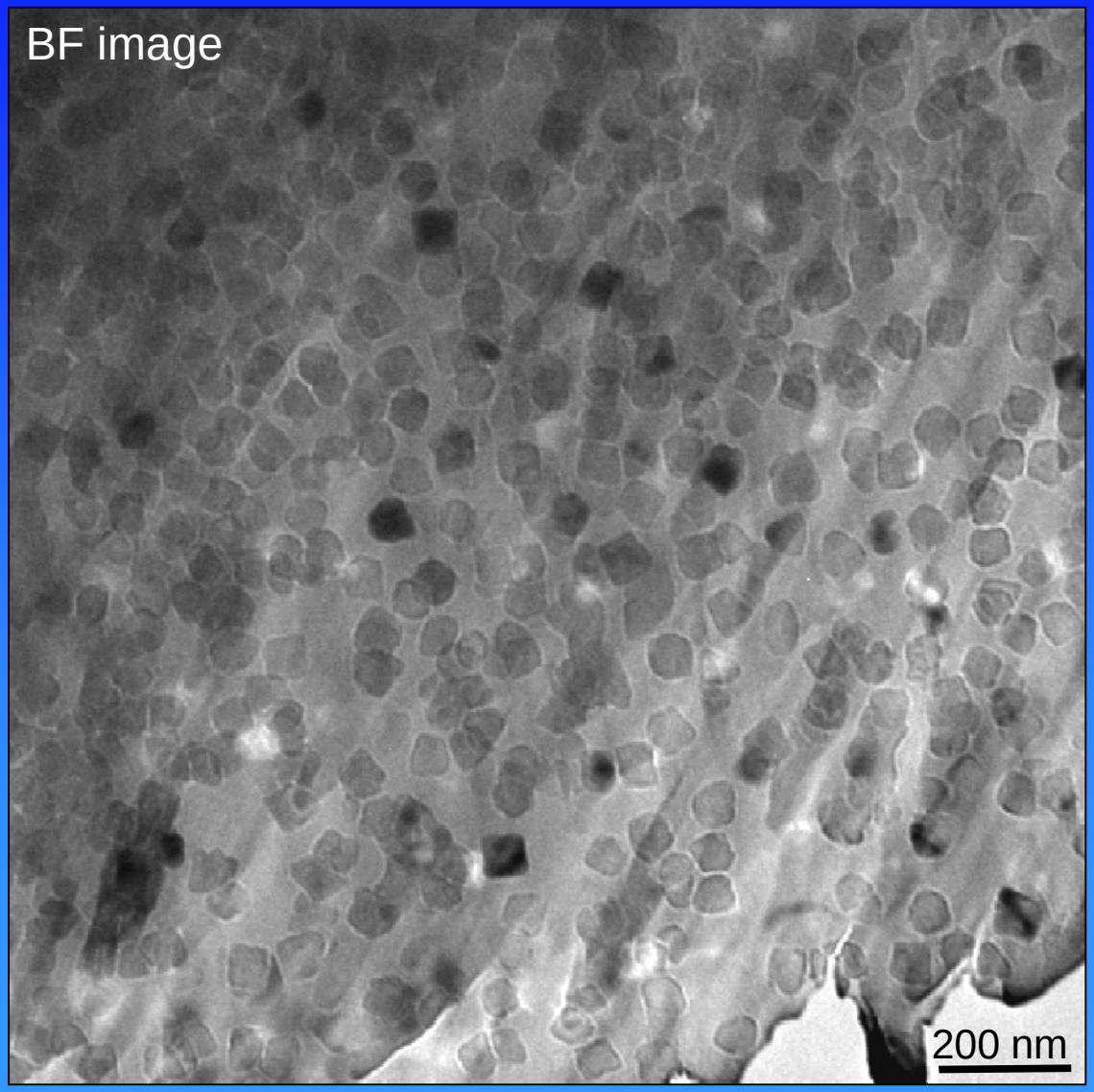


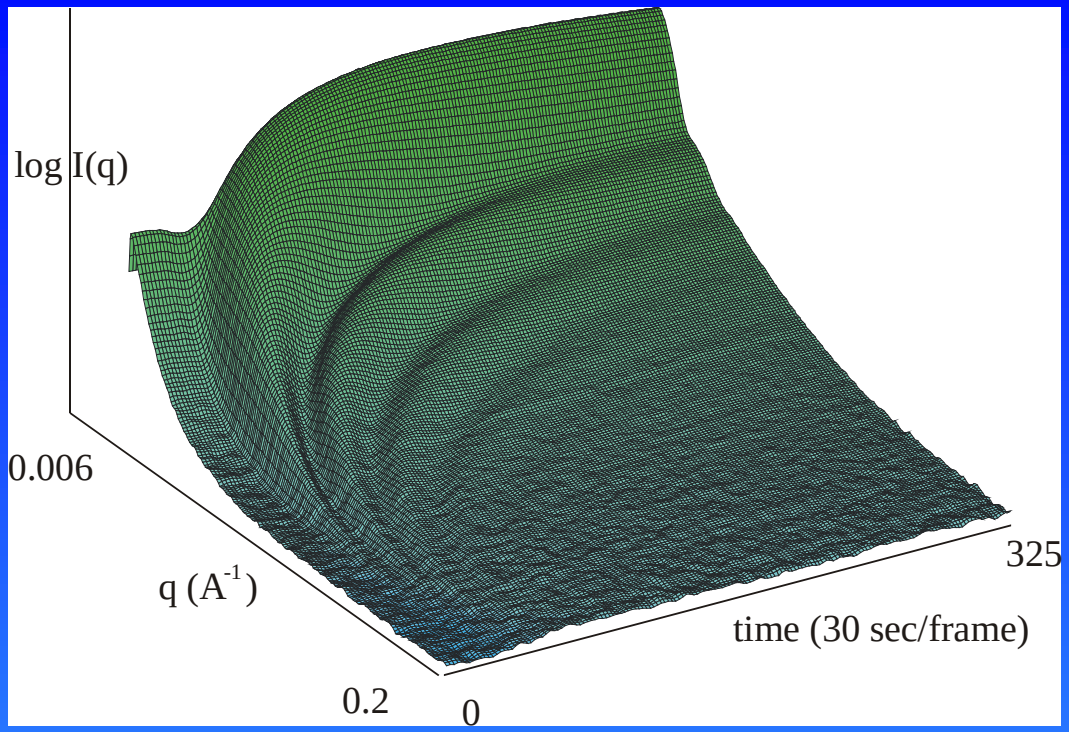
SAXS

WAXS

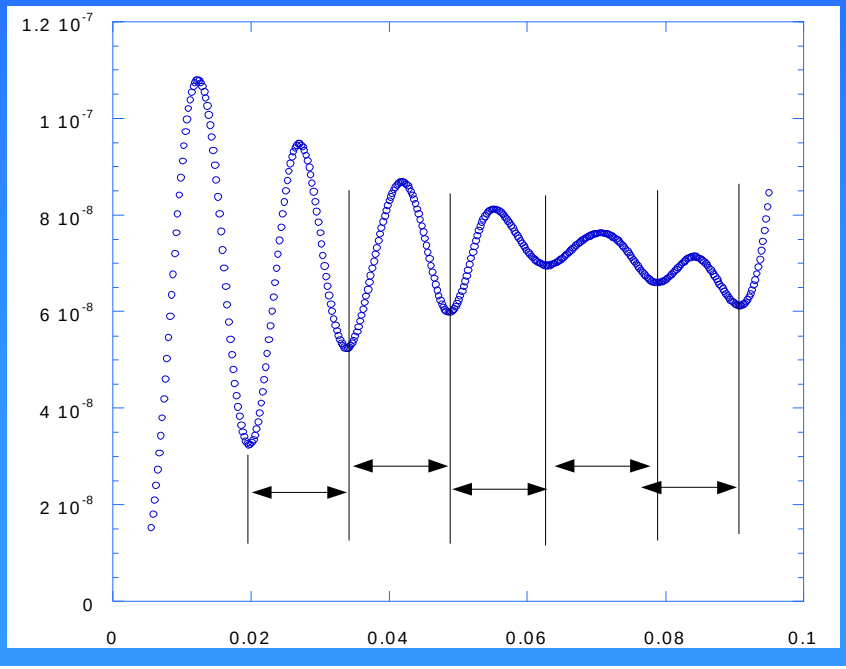


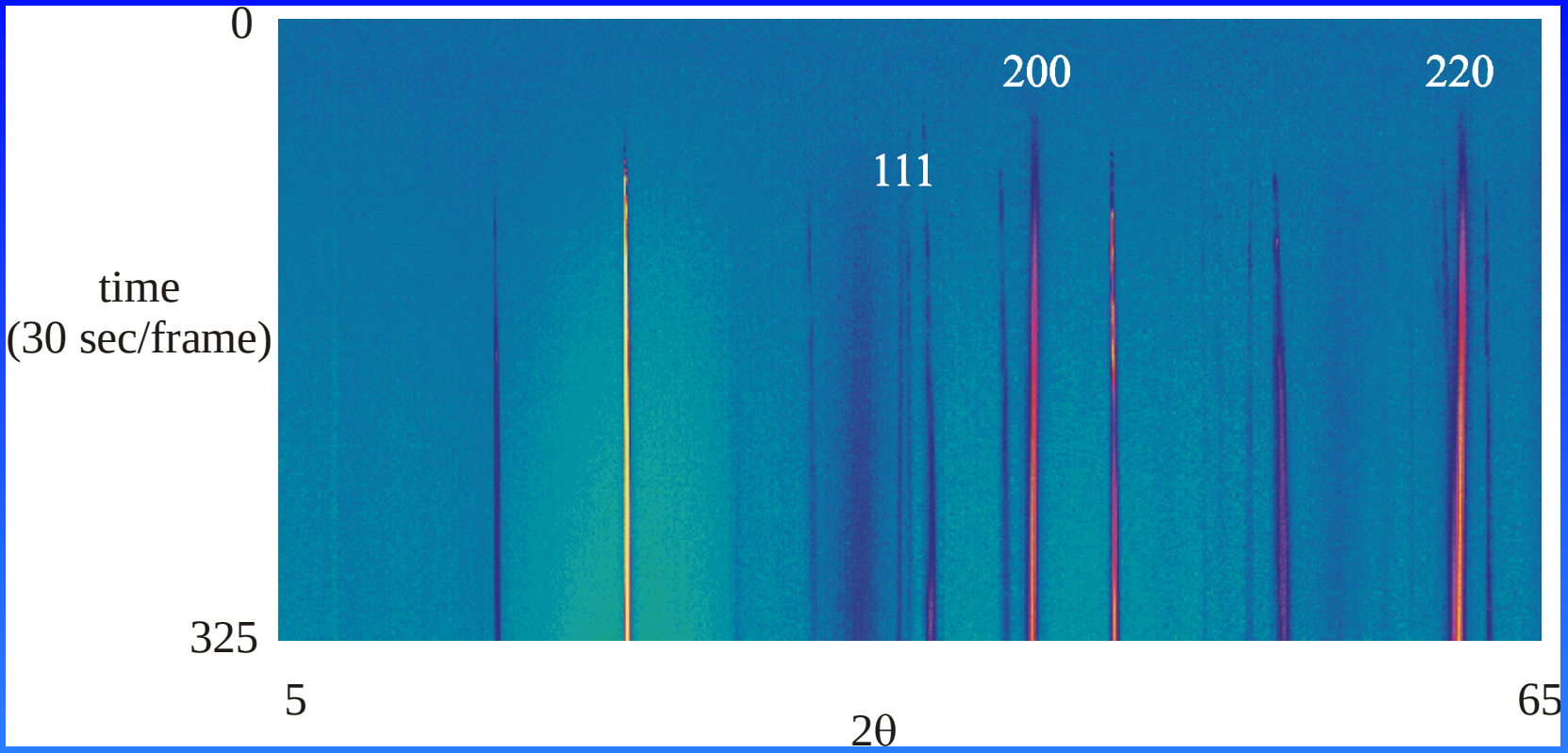
- TEM provides a very detailed picture of a small area
- SAXS provides a statistically average of a larger area

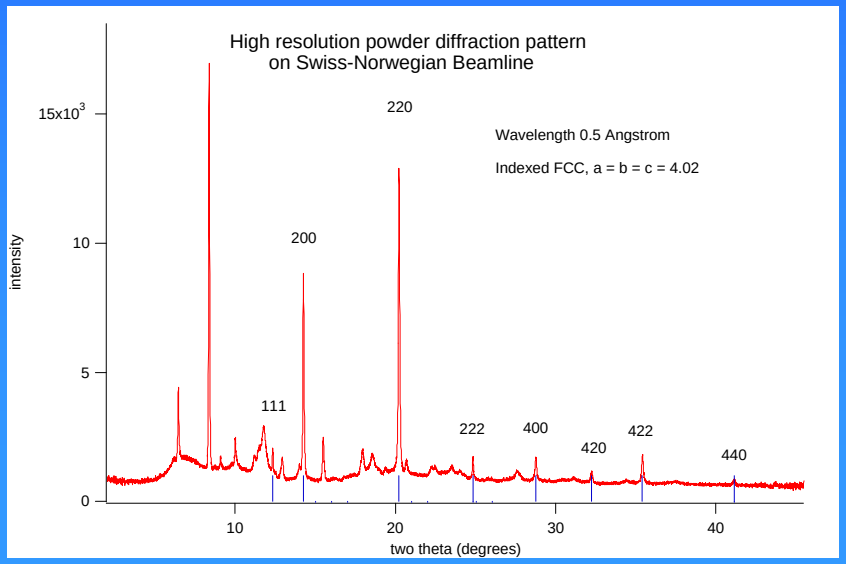

BF image
200 nm



$$I(q)=\langle n_e \rangle^2 F(q) S(q)$$




0
200
220
111
time
(30 sec/frame)
325
5
65
2θ


High resolution powder diffraction pattern
on Swiss-Norwegian Beamline
Wavelength 0.5 Angstrom
Indexed FCC, a = b = c = 4.02
15x10^3
10
5
0
intensity
111
200
220
222
400
420
422
440
10
20
30
40
two theta (degrees)

Synchrotron Radiation beamlines

- Can induce radiation damage
- Can be used to study damage
  - Longe range via scattering/diffraction etc.
  - Short range via XAFS, PDF etc.

Literature

- Giorgio Margaritondo
  - Introduction to Synchrotron Radiation
- Philip Duke
  - Synchrotron Radiation: Production and Properties

First is good for the general principles

Second is good if you like mathematics

But there are plenty of other books….

Thanks for your attention